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EVALUATION OF INITIAL PAVEMENT SMOOTHNESS FOR THE DEVELOPMENT OF PCCP CONSTRUCTION SPECIFICATIONS

Special Report

Final Report: Phase I

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16. Abstract

The Arizona Department of Transportation (ADOT) uses the California Profilograph and the K. J. Law 690 DNC Profilometer for measuring pavement roughness. However, ADOT has not used the profilometer on Portland Cement Concrete (PCC) pavement construction contracts because the current smoothness specifications are given in terms of the California profilograph index (PRI). This study was initiated to determine the feasibility of including the profilometer as one of the principal roughness measuring devices and of revising the current smoothness specifications. To accomplish that objective: (i) PCC pavement sections were selected for use in the testing of the K.J. Law profilometer and the California profilograph, (ii) pavement roughness data were obtained from the selected sections by both the profilometer and profilograph, and (iii) precision and correlation analysis were conducted for the two types of devices. In addition, an existing profilograph calibration program developed by the Pennsylvania Transportation Institute (PTI) was reviewed.

It was found from this study that: (i) The format of data from ADOT's profilographs and profilometer were not compatible with the PTI programs. Therefore, the PTI profilograph calibration procedure could not be used with ADOT's devices, (ii) Between 3 to 5 replicates are required to obtain a good estimate of the PRI, and (iii) A good linear relationship is obtainable between the mean values of profilometer Mays index (MI) and PRI and also between the profilometer International Roughness Index (IRI) and PRI values. The coefficients of determination, R^2, obtained for the regression models developed during this study were 0.95, 0.93, 0.95 and 0.68 for the regressions of Mays vs. PRI, IRI vs. PRI (for both wheel paths), IRI vs. PRI (for the left wheel path) and IRI vs. PRI (for the right wheel path), respectively.

On the basis of this study, it was concluded that: (i) it is feasible to calibrate the California profilograph by the profilometer, (ii) it is not practical to interchangeably use the profilometer and profilographs without instituting a significant modification to the current ADOT smoothness specifications, and (iii) the profilometer must be calibrated first before it can be used to calibrate profilographs. Further, it is recommended that generalized use of these results (for all profilograph devices) should be preceded by a validation study and that the ADOT pavement smoothness specifications be modified to reflect the precision capability of the smoothness measuring equipment currently in use.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

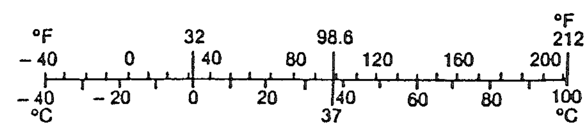
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1

INTRODUCTION

Background

Amongst the devices operated by the Arizona Department of Transportation (ADOT) for pavement roughness measurements are the maysmeter, the California profilograph, and more recently the K J Law profilometer. Pavement roughness measurements obtained using these devices can be employed to accomplish any one of the following functions.

1. quality control during construction,
2. acceptance at project completion time, and
3. condition monitoring and maintenance requirements.

For the most part, ADOT's use of the devices has been for acceptance measurements. Differences in the performance characteristics of the equipment means that they are not equally suited for different operating environments. The California profilograph for instance, is operated by pushing the device while steering along one of the wheel paths. The KJ Law profilometer is a much heavier equipment, installed in a van and operated at highway speeds (normally at 50 mph). Pavement smoothness specifications for asphalt concrete pavements based on profilometer measurements are already in place. Portland cement concrete pavement specifications (currently based on profilograph index values) are under review. The findings from this study will be used to facilitate the review process. See references for details on equipment operating characteristics [1, 2, 3].

During the summer of 1992, ADOT introduced its new Asphalt Concrete (AC) smoothness specification, providing for performance bonuses and penalties. Two construction projects were built using these specifications. Neither of the construction projects resulted in an appreciable bonus. Each of the contractors attained smoothness values just slightly better than what had been specified as the norm. Roughness measurement was performed with a KJ Law 690 DNC Profilometer.

At the same time, concern was expressed regarding the reproducibility of profilograph test results for concrete pavement acceptance. Subsequently, ADOT began evaluating the feasibility of performing final acceptance of concrete pavement smoothness with a KJ Law 690 profilometer.

Incentive / Disincentive Scheme

ADOT currently has an incentive/disincentive scheme in place for its Portland Cement Concrete Pavement (PCCP) construction contracts. Upon completion of contract works, contractors are thus rewarded with a bonus for quality of work that exceeds the nominal 'preferred' quality. Similarly if quality is below this measure, the contractor is penalized for the shortfall in quality. At the moment the PCCP construction specifications are in California profilograph index (PRI) units. The Department would like to have the specifications in both PRI and in profilometer equivalent measures so that the concerned parties can use either of the devices for purposes of controlling or verifying these measurements.

Roughness Measurement Units

Apart from the different physical characteristics and speed of operation, the California profilograph and the profilometer are designed to produce pavement roughness values in different units. The California profilograph computes a California profilograph index (PRI) for the full length of the run, in inches per mile. Typically these values are between 0 and 15 in/mile, and runs are 0.1 miles long. The profilometer on the other hand, can be set to compute either a Mays index or an International Roughness Index (IRI) or both. The index values from the profilometer can be reported for desired section lengths irrespective of the total length of the run. Since the equipments are used for the measurement of the same pavement characteristic, that is roughness, and noting that different equipments may be used for the same section at different times, a relationship between the different measurements becomes a vital link for the comparison of such measurements. This requirement constitutes an important task toward the objective as stated in the next section.

Project Objectives

To develop smoothness specifications for Portland Cement Concrete pavements. To be able to accomplish the stated objectives, the following tasks were proposed as being an important part of the research project;

- Review the average roughness values determined during acceptance testing for the concrete pavements constructed since 1986 in the Phoenix area.
- Select concrete pavement sections which represent several roughness levels typically encountered during new construction. Test these

pavement sections with both the profilograph and profilometer devices.

- Develop a correlation between PRI established by the profilograph and Mays roughness or IRI established by the profilometer using field data.
- Develop a means for calibrating a profilograph to a known standard, preferably the KJ Law profilometer.

Scope

This phase of the study covered the following topics:

1. An investigation of possible approaches for the calibration of California Profilograph devices.
2. A study of the Correlation between California Profilograph roughness measurement values (PRI) and Profilometer roughness measurement values (Mays and IRI).

With regard to profilograph calibration, the study aimed at investigating the suitability of a variety of calibration approaches for possible use within the Arizona Department of Transportation. Since ADOT uses its own equipment in pavement quality control measurements, the department has the responsibility to calibrate the equipment. The study looked at a number of suggested procedures for their possible use in profilograph calibration. These are described in the next chapter.

The correlation study serves to establish a statistically valid expression for one roughness index measurement as a function of the other, if such a relationship is found to exist. Having established such a correlation it is then possible to compare roughness measurements originating from the two systems. Field data collected with both devices were used for the correlation.

CHAPTER 2

REVIEW OF PROCEDURES FOR THE CALIBRATION OF CALIFORNIA PROFILOGRAPH DEVICES

The calibration of a measuring device assumes that one has a means of determining the true value of the parameter being measured. The true value can then be compared to the value obtained with the measuring device. Depending on the nature of this measurement, and the established cause of the observed difference from the true value, appropriate corrective measures are taken. Alternatively, if an observed deficiency on the device(s) is known to result in systematic errors, a correction factor can be applied to the output from the device.

In this study, the following procedures were investigated to determine possible use towards profilograph calibration.

1. Pennsylvania Transportation Institute (PTI) program for the simulation of a California profilograph
2. PTI program for computation of a California profilograph index
3. Use of profilometer profile data with PTI profilograph index computation program

A description of the procedures, their underlying assumptions, limitations, observed problems, and the results of test runs are given in the next sections. Appropriate comments are made regarding the use of the respective procedures.

PTI - Program for the Simulation of California Profilograph

The function of this computer program is to simulate and evaluate the profile as would be measured by a California profilograph with 2, 4, 6, 8, 10, or 12 supporting wheels. Measuring wheel tire wear and eccentricity can be incorporated. One can therefore use the program to modify the profile from a California profilograph in order to remedy known deficiencies of the device.

This program was written by Kulakowski and Wambold in 1989 [1], for use in adjusting the profile obtained using a profilograph so as to correct for such device parameters as tire wear and wheel eccentricity. The program uses as input, a stream of profile data obtained with a California profilograph device of specified characteristics to makes corrections for device deficiencies, and output the profile data as would have been recorded by an ideal profilograph. The program requires the following input variables which describe the California profilograph device used:

- total number of wheels on the right (must be even),
- total number of wheels on the left (must be even),
- length of the main truss (feet),
- distance between wheels on the right (feet),
- distance between wheels on the left (feet),
- tire wear quantity for the radius of the measuring wheel (inches), and
- eccentricity of the measuring wheel (inches).

Also required is an existing file containing the profile data stream and a filename for output of the resulting profile data. The program assumes a sampling distance of 6 inches for the input data. The program only compensates for wheel tire wear and eccentricity of the measuring wheel, both given in inches. If tire wear and eccentricity values are both zero, the output profile is the same as the input profile.

As mentioned above, the program requires 6 inch spaced profile elevations from the California profilograph as input. The profilographs used by ADOT give only one normalized roughness index value in in/mile for the entire length of the section measured. The necessary data for input into this program was thus not available.

The problem of input requirements aside, the determination of tire wear and wheel eccentricity is not an easy task to accomplish. The wheel tire is normally replaced when it becomes noticeably worn. It is also documented in the same report that tire wear, when it is uniform, has no significant effect on roughness measurements [1].

PTI - Program for the Computation of Profilograph Roughness Index

This program is due to the same authors above [1]. The function of the program is to calculate roughness index for a given set of profile data using California or Rainhart procedure. This is different from the program discussed in the preceding section in that it does not use as input the profile from a profilograph device. The program uses the actual elevations, the same elevations that are used by the profilograph devices. The previous program outputs a new corrected profile from the input profile while this program computes the profilograph index for the described section. The program, written in Microsoft FORTRAN for the IBM PC and compatible computers, was developed by Meau-Fuh Pong.

The program is designed to compute a California Profilograph Index or a Rainhart Profilograph Index from a set of raw profile data. The computer program requires input of profile elevations data at 2 inch intervals.

California vs. Rainhart Profilograph Index Computations

The program can be used to compute either a California Profilograph index or a Rainhart Profilograph index. The main differences in using the program for the two types of computations are as follows. First, the value of the blanking band - termed 'BLANK' in the program, is 0.2 for the California profilograph, and 0.1 for the Rainhart profilograph. Second, the length of the main truss of the profilograph - termed 'PGLEN' in the program, is 25 feet for the California profilograph, and 12.5 feet for the Rainhart profilograph. The two values are coded in the program and must be changed by editing the program source code before running the program for a different type of profilograph. A block diagram of this program is shown in Figure 1. A detailed description of the program is provided in Appendix A.

Typical Test Section for Index Computation

The profilograph roughness index computation program was developed for use where a test section of known elevations exists. The known elevations are input to the program which computes the appropriate profilograph index. The profilograph device to be calibrated is used on this section and the resulting index is compared to the computed value to determine a calibration procedure for the device. Typical examples for such test sections are suggested by the authors as: 1) a sinusoidal profile, and 2) a horizontal section with rectangular bumps at particular locations. In view of the difficulty in the manufacture of a sinusoidal section, the rectangular bumps are a more practical alternative. In this study, the profile elevations from a horizontal section with rectangular bumps were used to verify the performance of the program against the given theoretical index.

According to the authors, the section shown in Figure 2 has a theoretical California profilograph index of 14.67 in/mile. The elevation data corresponding to this section were generated, written on a data file and used with the PTI program. The program computed PRI value for the test section of 14.55 in/mile. Figure 3 shows a summary of the program output.

The author stresses the fact that to get the index of 14.67 in/mile the section must start with the 30 foot flat section, have a 30 foot bump, followed by a 30 foot flat section as shown in Figure 2. The height of the bump may vary between 0.4 and 0.5 inches. This is the section which was used to obtain the 14.55 in/mile shown in the output of Figure 3. Sections with more than one bump resulted in different index values, and so did sections with different bump heights, as discussed under the next sub-heading.

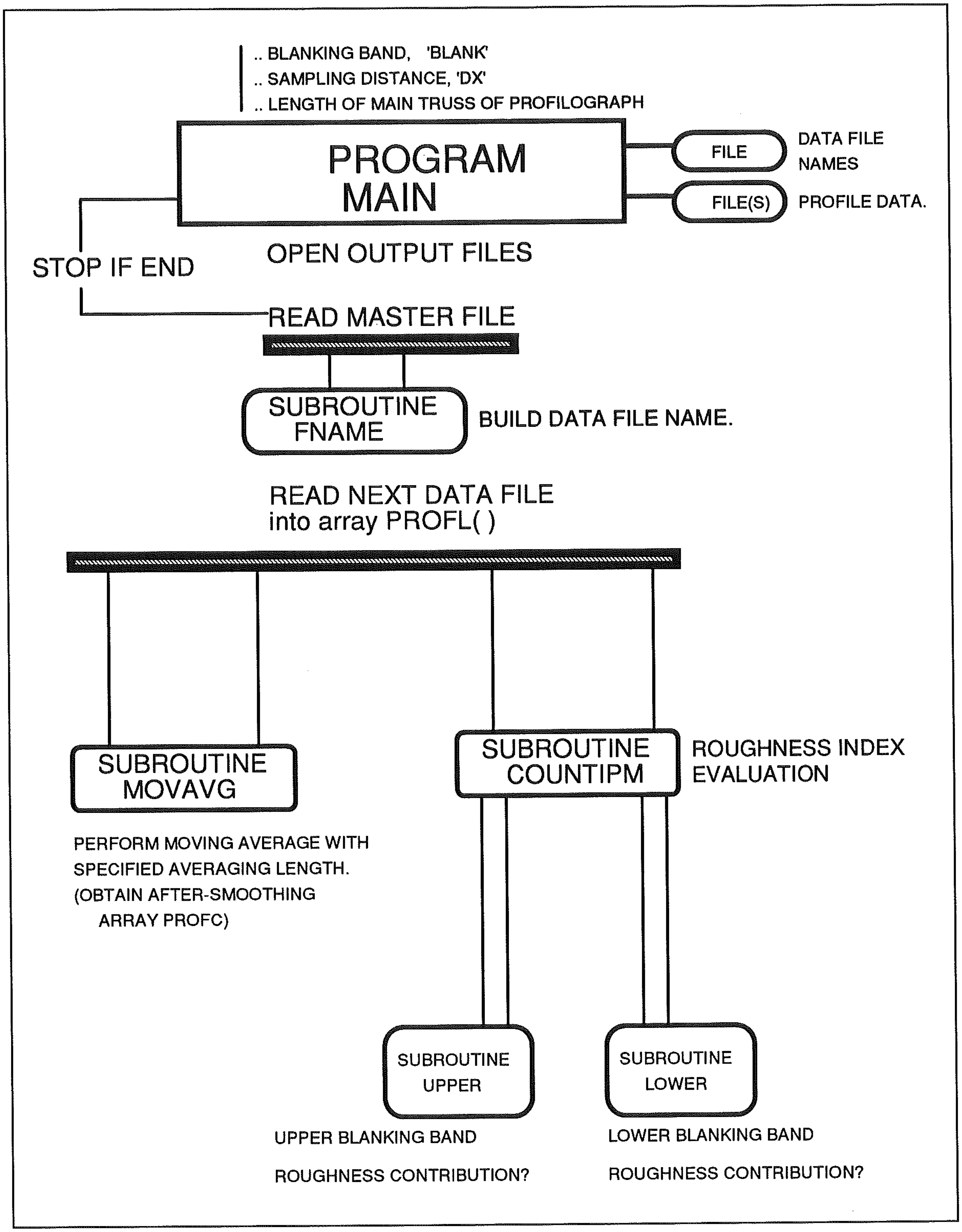

Figure 1. Block Diagram of the PTI - Program for the Evaluation of Profilograph Roughness Index

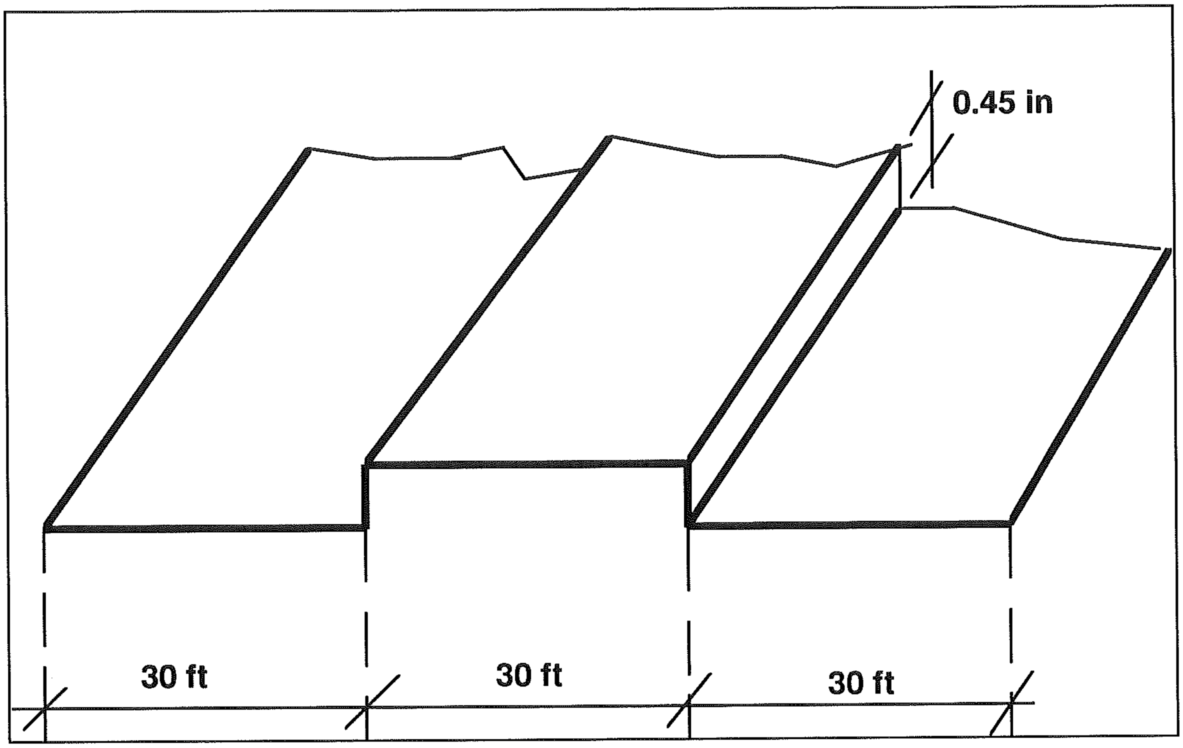

Figure 2. Suggested Test Section for Profilograph Calibration

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CALIFORNIA INCHES PER MILE FROM COMPUTER RESULTS

                  FILE : STEPC1.DAT

   16. TO    30. FOUND - .1248 ROUNDED TO    .10
   60. TO    74. FOUND - .1233 ROUNDED TO    .10
    ACCUMULATED CONTINUOUS INDEX :    .248

     ACCUMULATED ROUNDOFF INDEX :    .200

  OVERALL DISTANCE =    90.0 FEET OR  .017 MILES

  THEREFORE, CONTINUOUS INCHES PER MILE = 11.733
       AND DISCRETE INCHES PER MILE =14.550
```

Figure 3. Program Output for the Suggested Test Section

Variation of Bump Height and use of 6 inch Sampling Interval

Using elevation data points at 2 inch intervals, the program produced a PRI value of 14.55 in/mile. The given theoretical value for the index is 14.67 in/mile. It is not clear at this point what caused the discrepancy in the values. The same section was used to investigate the effect of 6 inch interval sampling. This is the interval at which roughness profile data is reported by ADOT's profilometer. In one case, elevations at 6 inch intervals for the 90 feet length of the section were directly used with the original program. In another case, the same data were used with the modified program so that linear interpolation to 2 inch interval elevations, was performed in advance of the index computation.

To investigate the sensitivity of the program, the bump height was varied from 0.4 inch to 0.5 inch. The interval was selected because the authors of the program claimed that bump height variation within the interval will not produce variation in the value of the profile index. Index values were computed for bump heights of 0.400, 0.425, 0.450, 0.475 and 0.500 inches. Although the author claims that the index value will be the same for all bump heights in the 0.4 and 0.5 inch interval, the results from this study, which are tabulated in Table 1, contradicted that claim.

TABLE 1. PRI VALUES FOR TEST SECTION COMPUTED FOR 2 INCH AND 6 INCH SAMPLING INTERVAL

	SAMPLING INTERVAL FOR ELEVATION DATA		
BUMP HEIGHT (in)	2" INTERVAL DATA	6" INTERVAL DATA WITHOUT INTERPOLATION	6" INTERVAL DATA WITH INTERPOLATION
0.400	11.6	29.3	17.3
0.425	13.1	32.3	19.7
0.450	**14.6**	35.2	21.7
0.475	16.0	38.1	23.9
0.500	15.5	41.1	26.1

From these results it was not possible to make a conclusive statement regarding the usefulness of the interpolation procedure for converting the profile elevation data given at the 6-inch intervals to profile data at 2-inch intervals.

Use of Profilometer Data

Having checked the program using elevation data for the suggested test section, the program was tested with profilometer data. For the purpose of this study, the profilometer data were assumed to represent the 'true' profile elevations for the sample section. Since the PTI program requires data input at 2 inch intervals, and since the profilometer data are given at 6 inch intervals, it was necessary to interpolate the profilometer data. For each successive pair of profilometer data points, a linear interpolation was performed to generate two more points in-between as shown in Figure 4. This modification was made in the program after the data file had been read, but before the calculation of the total distance. The array size of profile elevations was thus expanded three-fold. All other aspects of program logic were unaltered. The modified data from the profilometer were then used as input to the profilograph program. The simulated index value with this program was then compared with actual index values obtained with California profilograph.

The index values obtained using the modified program with data from the profilometer are summarized in Table 2, and plotted in Figure 5. The results are based on a sample data set for profilometer profile measurements for a 0.1 mile project section.

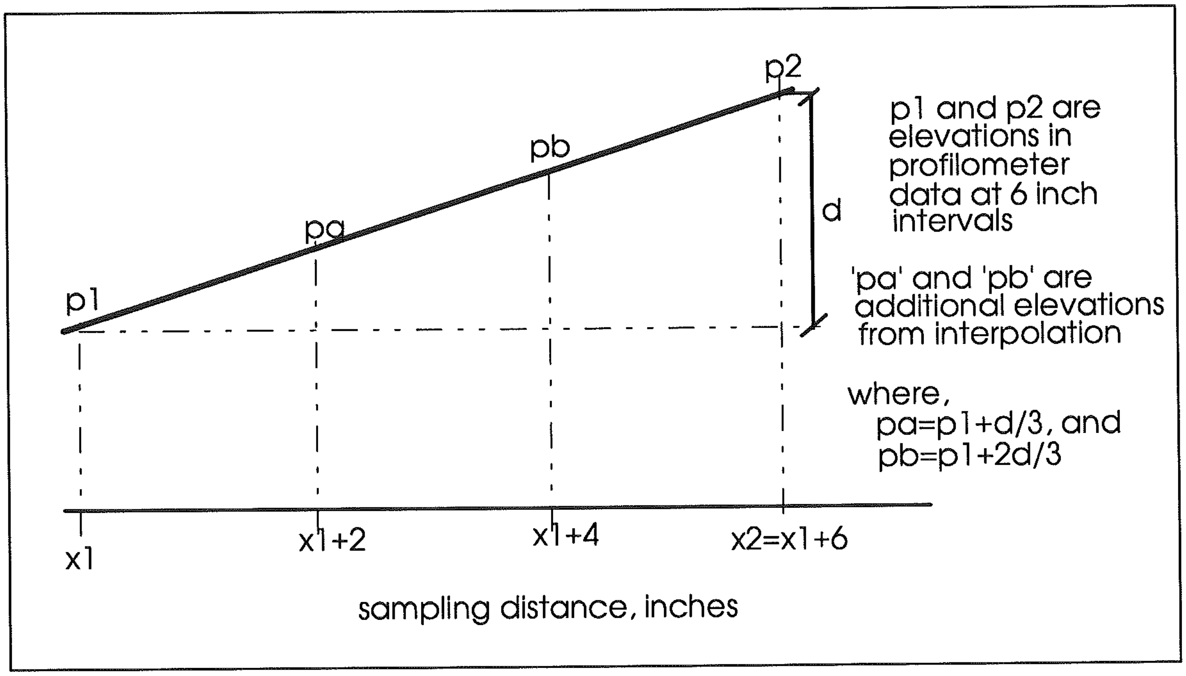

Figure 4. Interpolation Procedure for Profilometer Data

TABLE 2. COMPUTED PRI INDEX, MEASURED PRI INDEX AND PROFILOMETER IRI FOR SELECTED PAVEMENT SECTIONS

Measured PRI - in/mile	3.0	7.0	4.0	8.0
Computed PRI - in/mile (PTI - program)	**0.6**	**3.0**	**3.4**	**8.5**
Profilometer IRI Index - in/mi (Using same data as above)	75.3	83.5	78.2	93.0

(see also Figure 5 and 6)

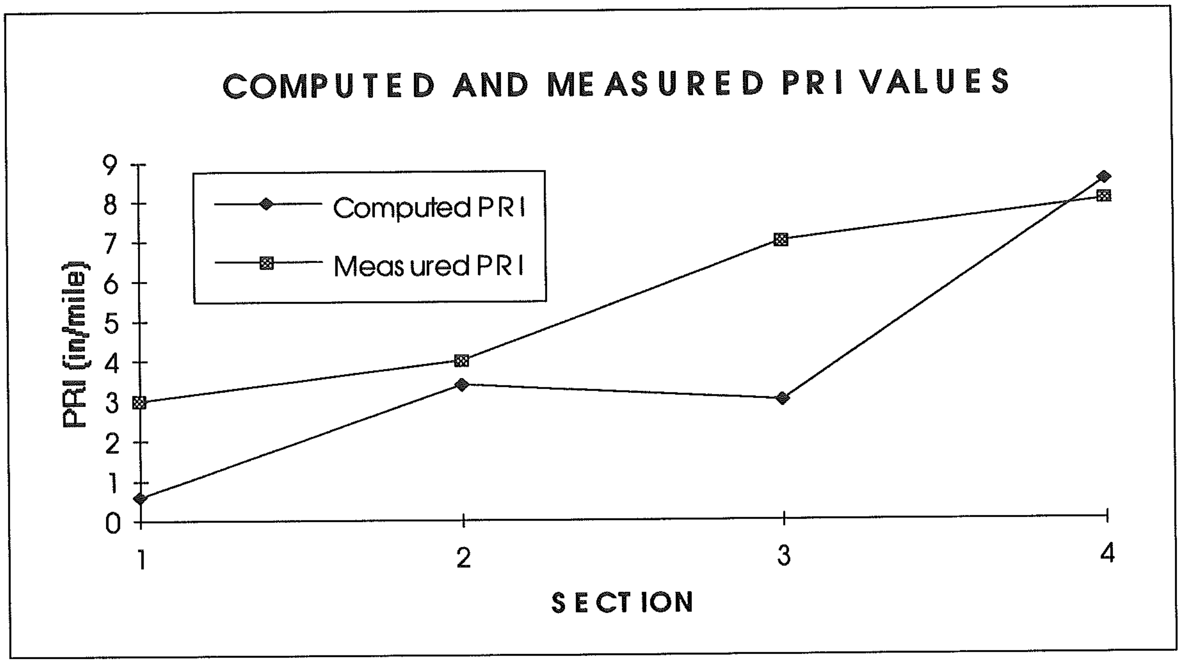

Figure 5. Trend of Computed and Measured PRI for Selected Sections

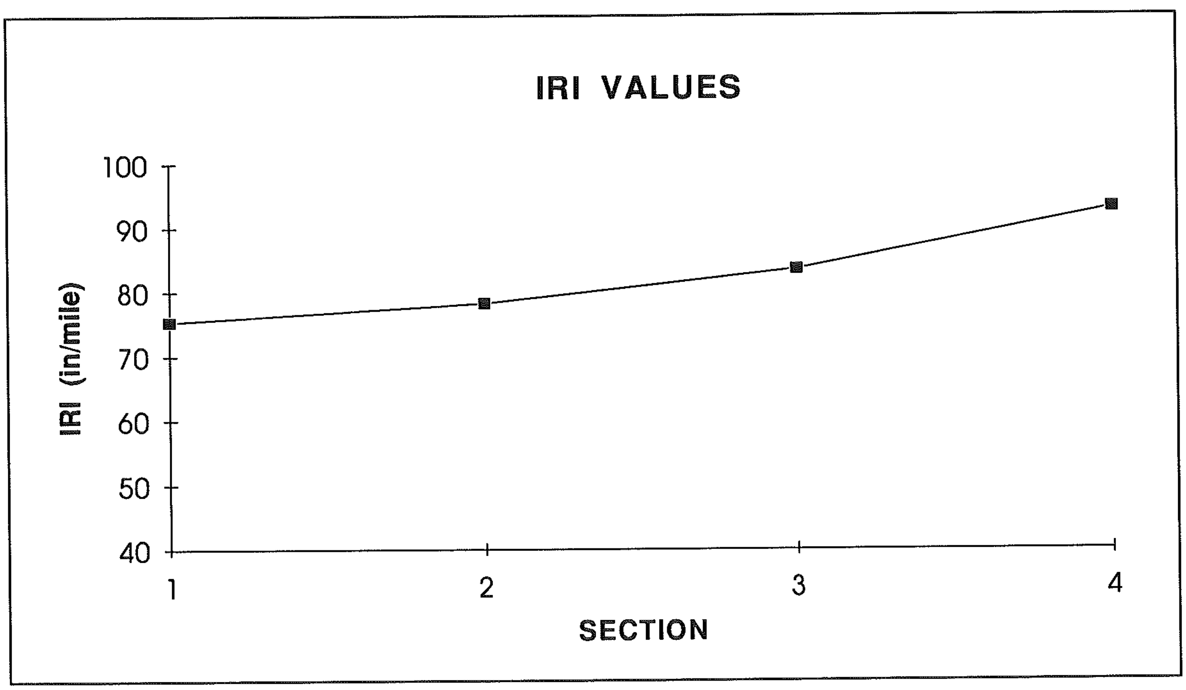

Figure 6. Trend of Profilometer IRI for the same Sections of Figure 5

Summary of Observations

1. The PTI profilograph index computation program computes the California profilograph roughness index for the given test section to a value very close to the that of 14.67 in/mile given by the authors. However, this value was only obtained for a bump height of 0.45 inches. For other bump heights, including those in the range 0.4 to 0.5 inches (for which the authors claim the Index should remain the same), different index values were obtained.

2. The direct use of profilometer data (6 inch interval) as input into the PTI profilograph index computation program resulted in index values much higher than the expected magnitudes. This led to some program modifications for transforming the data to the equivalent of 2 inch interval elevations by interpolating between each pair of successive data points as illustrated in Figure 4. While this modification did lower the computed index values, a trend of computed values corresponding to the measured values was not visible.

3. When the modified program was used with profile elevation data at 6 inch intervals for the 90 foot test section, the index value obtained for a bump height of 0.45 inches was 21.7 in/mile instead of the 14.67 in/mile. The computed index values with interpolation were generally about 1.5 times larger than those obtained with the 2 inch interval elevation data, as seen in Table 1, columns two and four.

4. The observations in (2) and (3) above strongly indicated that the 6 inch - interval format of the profilometer elevation data was not appropriate for use in PRI computation with the PTI program. A linear interpolation performed to obtain elevation data at 2 inch intervals could not remedy the problem.

CHAPTER 3

CORRELATION STUDY: EXPERIMENTAL DESIGN AND DATA COLLECTION

Background

In a preliminary investigation of the correlation between profilometer roughness index values (Mays/IRI) and California profilograph index (PRI) values, roughness data using California profilograph devices were sampled from project measurements taken a few months earlier. The results of this exercise suggested very poor correlation between the measurements. When split into individual projects, some plots even looked like a random scatter of data points. It was strongly felt that the problem was due to the variability of California profilograph roughness measurements, as it was realized that the roughness index values were obtained from a single measurement using the California profilograph. The repeatability standard deviation for these devices, which is discussed in later sections, was found in a separate study to be around 0.85 in/mile [4]. The PRI values associated with the 0.85 in/mile repeatability standard deviation were within a 2.0 in/mile to 14.0 in/mile range.

The low precision of the California profilograph made the use of single measurement from the device for correlation analysis statistically inappropriate. However, since both devices were measuring the same physical quantity, there was reason to expect correlation between the measurements obtained with the two types of devices. It is on the basis of this reasoning and results from previous studies that this correlation study was initiated. Previous studies [3, 5] showed that there was indeed correlation between profilometer and profilograph roughness indices.

The following needed to be determined with respect to the correlation analysis;

- the variables in the regression analysis
- the units of measurement for the above variables
- variable levels selected for the experiment
- the procedure for measurement of the different variables
- the number of measurements used in the analysis
- regression model and formulation of a hypothesis

Test Devices

The correlation study investigated the correlation between profilometer pavement roughness index values (Mays / IRI) and profilograph PRI values. Since the principal objective was to establish the existence of correlation, it was decided to initially use one profilometer (the only available) and one profilograph. By using only one of each device type, the requirement of the initial amount of data was kept to a minimum.

Pavement roughness index values obtained with the profilograph and the profilometer are both expressed in in/mile. The former is referred to as a California Profilograph Index, PRI, while the latter is computed as either a Mays Index or an International Roughness Index (IRI). Although the units for these indices are the same (in/mile), the magnitudes are very different. Typically, PRI values for new PCC pavements have been found to lie in the range between 0.0 in/mile and 15.0 in/mile. The corresponding Mays index values have been found to lie in the range between 40 to 120 in/mile. Therefore, it may be said that the magnitudes of Mays index values are approximately 10 times larger than the corresponding PRI values. Likewise, corresponding IRI values are only slightly larger than Mays index values.

Pavement Roughness Levels

The importance of identifying the possible range of roughness values was based on how the results of the analysis can be generalized over this range. For instance, if the response variable behaves as shown in Figure 7, it is clear that relationship between the independent and the response variables will depend on the sampling coverage on the independent variable.

In the example depicted in Figure 7, if one only makes use of data for levels between 'a' and 'b' for the independent variable, variable 1, the relationship would most probably be considered linear. However, the inclusion of data from higher levels of this variable (between 'b' and 'c') would show that a linear model based on untransformed data would not represent well the relationship of these variables. For the purpose of this study, it was believed that satisfactory results could be obtained by sampling highway pavement sections that were representative of low, moderate, as well as high pavement roughness.

Precision of Roughness Measurements

Precision refers to the degree of closeness between replicate measurements. A measuring device has high precision if replicate measurements yield the same values or very small variations. The measuring device has low precision if the values of replicate measurements have relatively high variations.

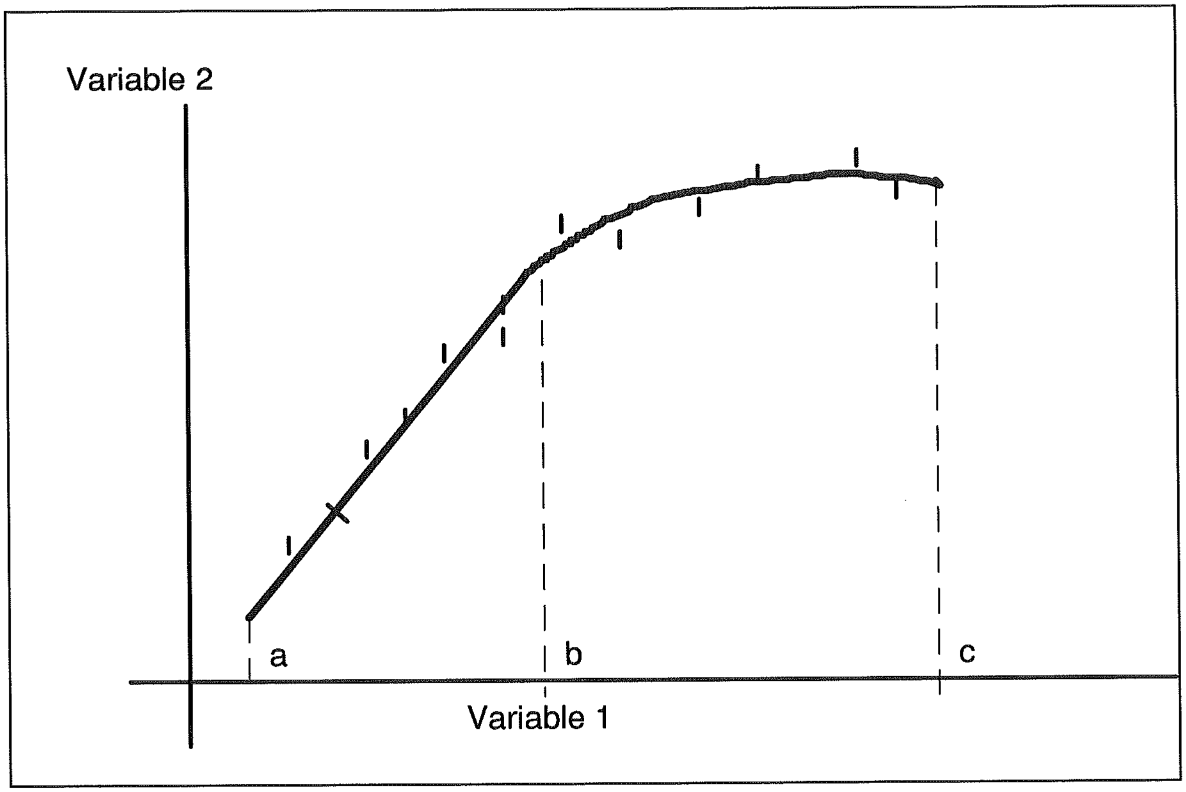

Figure 7. Possible Error in Generalizations Based on a Limited Range of Variable Values

ADOT presently uses a KJ Law profilometer, model 690-DNC and California profilographs for measurement of pavement roughness. The output from the profilometer analysis program includes a Mays Index and an IRI Index. To be able to make a statement about the precision of pavement roughness measuring devices, an analysis was made on the variation of roughness measurements for different passes (runs) on the same lane section. These variations, at different levels of pavement roughness, were compared to determine whether a general statement regarding measurement repeatability standard deviation was justifiable. For the analysis of profilometer repeatability the Mays Index was used.

Profilometer Repeatability

Repeatability is a measure of precision when the operating conditions are unchanged. For the measuring devices, repeatability is a measure of the ability of the device to repeat the same measurement under similar operating conditions within a short interval of time. The time interval is important to ensure that changes in environmental conditions like temperature, humidity etc., do not affect the performance of the measuring device.

The repeatability of profilometer roughness measurements was investigated using data obtained from several pavement sections. Profilometer data were collected in three replicates from each section. Similar evaluations for profilograph devices have been conducted [2, 4] during which the following values were obtained:

- section average roughness measurement
- section roughness measurement standard deviation
- section roughness measurement variance

For the collective set of data, the pooled standard deviation was then evaluated using the individual section variances. The usefulness of the pooled standard deviation was investigated and a confidence interval was developed at the 95% level for pavement section roughness measurements.

For this data, the mean roughness measurements (Mays index) for the twelve sections ranged from a 41 in/mile to 122 in/mile. The variation in the roughness between sections was to be expected in view of the process used in selecting these sections, which sought to include sections representative of the different roughness levels. A plot of the standard deviations for the repeat measurements within a section against the mean roughness for the respective section showed no standard deviation trend with changing roughness values. This important observation was the basis for the use of the pooled standard deviation as a good measure of the repeatability standard deviation, S_r, across the different roughness levels. The value of S_r was determined to be about 2.07 in/mile by the expression given below.

$$S_r = \sqrt{\frac{\sum_1^N S_i^2}{N}}$$

where: $S^2{}_i$ = standard deviation for sample i

N = number of samples

The repeatability limit, r, can be computed from the equation $r = 2.8\ S_r$, which in this case results in a value of r= 5.8 in/mile (at the 95 % level). The 5.8 in/mile repeatability limit provides that, when a sufficiently large number of replicates are taken, 95% of the time the difference between any two such replicates will not exceed 5.8 in/mile. These limits should be viewed in the light of the actual magnitudes of the measurements involved, the magnitudes of profilometer Mays index values being typically ten times or more larger than profilograph PRI values.

Profilograph Repeatability

The average repeatability standard deviation of the California profilograph device, according to the data collected in this study was 0.53 in/mile. Using this value and the expression for the repeatability limits presented above, the corresponding repeatability limit would be 1.48 in/mile. The profilometer and profilograph repeatability limits should be viewed in the light of the actual magnitudes of the corresponding index values as obtained using the respective devices. For instance, whereas the mean PRI value for the roughness data in the 1990 study was 4.13 in/mile, the mean Mays index value for the same pavement sections was 66.5 in/mile. In this case, the computed relative repeatability limits were about 9% for the profilometer and 36% for the profilograph. The relative repeatability limits were obtained by dividing the value of the repeatability limit by the mean index value obtained with the device.

Selection of Number of Replicates for Regression Data

This determination is an important consideration in determining the quality and usefulness of the results of the analysis. There are a number of different ways of obtaining the number of data points to be used in the regression. The most common of these are 1) Data points based on a single measurement value for each variable, and 2) Data points based on average values from replicate measurements for each variable. The first case would be appropriate only in a situation where measurements are obtained with very precise devices.

As seen from the preceding sections, profilograph and profilometer measurements are not easily repeatable. This means that two or three measurements taken under the same experimental conditions will not always produce the same values. A repeatability standard deviation was evaluated as a measure of the level of precision attainable with each of these devices. An individual measurement therefore, does not give us a good estimate of the true value of the roughness index. A good estimate of the value can be obtained using a large number of replications. Since under real life conditions a large number of replications may not be practical or economical, a compromise that allows some degree of error in the estimate is normally adopted. The compromise provides for the use of a feasible number of replicates. Figure 8 shows how the magnitude of the error of estimate for the mean PRI value, E, varies with the number of replications. The calculation of the error of estimate was based on a 95% confidence level and a repeatability standard deviation of 0.85 in/mile.

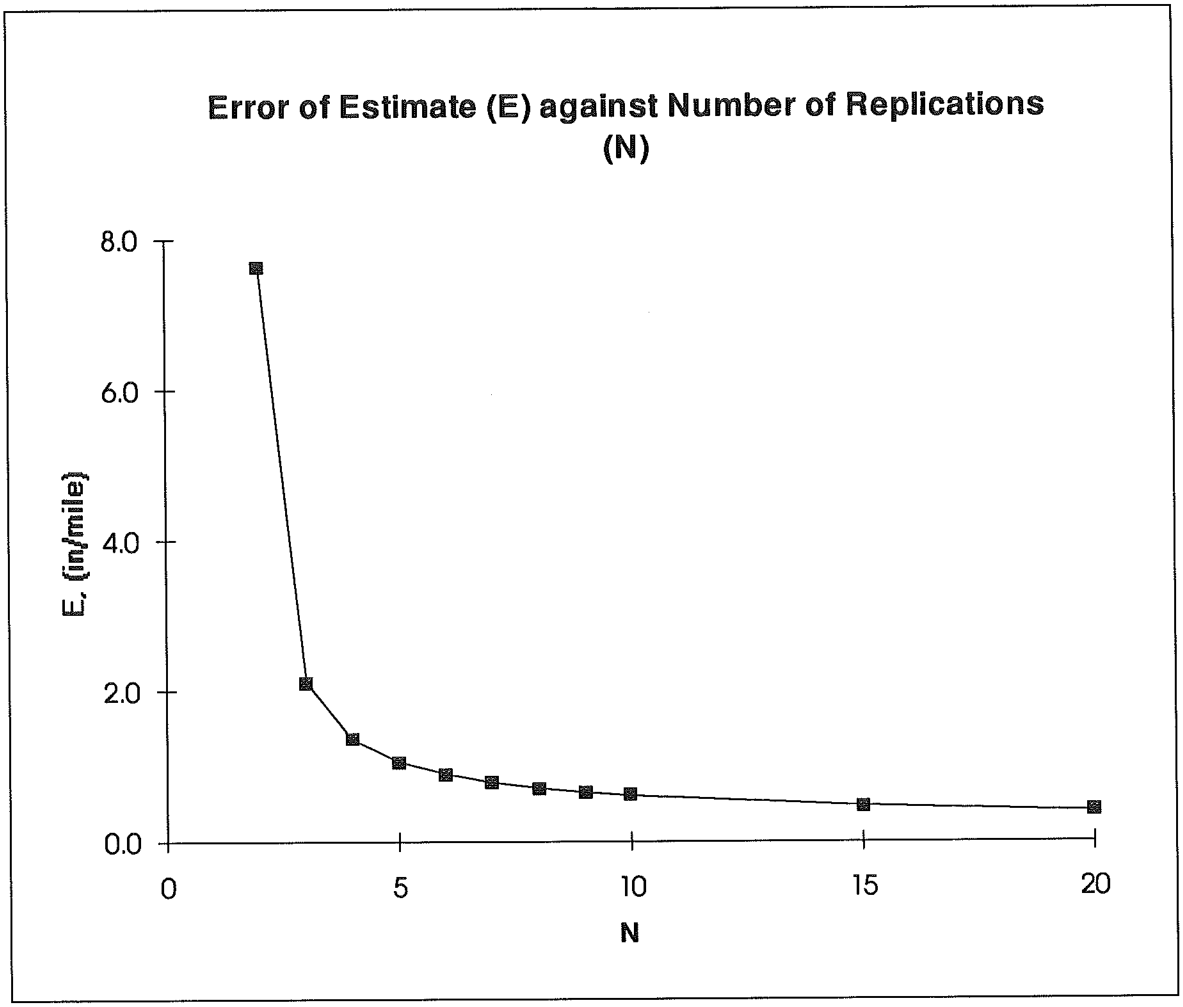

Figure 8. Error of Estimate for PRI against Number of Replications

The t - distribution approximates the distribution of the measurement values for each individual section in this experiment. The population mean is the hypothetical average measurement for a 0.1 mile section assuming a very large number of replicate measurements. An individual measurement can therefore lie anywhere in the range between -E and +E, 95% of the time. Depending on the number of replicates that can be made for each data point, it is possible to statistically determine the proximity of the computed mean to the theoretical mean. The width of the confidence interval narrows with increasing number of replications, approximately according to the following expression;

$$E^2 = \frac{t^2 * s^2}{n}, \qquad \text{for which} \quad E = \frac{t_{\alpha/2,n-1} * s_r}{\sqrt{n}}$$

where,

E = half width of the confidence interval, the permitted error for estimate of the mean.

s_r = the repeatability standard deviation (for one data set it is the standard deviation of the applicable measurements).

t = the value from the student t - distribution for the significance level and degrees of freedom (n-1) given.

n = the number of replicates used to estimate the parameter.

α = the significance level for which the confidence interval is desired.

According to a study on the precision of profilograph measurements [4], it was determined that the repeatability standard deviation, s_r, was approximately equal to 0.85 in/mile. In the above expression both the numerator and denominator changes for each 'n' value. In this case, the values of error of estimate, E, at the 95% were computed as:

- E = 2.11 for n = 3,
- E = 1.0 for n= 5,
- E = 0.6 for n=10, and
- E = 0.4 for n=20.

For purposes of this evaluation the effect of the number of replicates on the repeatability standard deviation is ignored. One observes that as we increase the number of runs beyond 10, the benefits per additional run in terms of a reduction in the confidence interval diminishes. At the same time the size of the confidence interval in relation to magnitude of variable values is between 10% and 20% for n=5, and between 6% and 12% for n=10, assuming pavement roughness index values between 5 in/mile and 10 in/mile, as typically obtained with California profilographs for new pavements. Therefore, the following recommendations were put forward;

- Using at least 5 passes for each lane section, the mean value can be expected to be within 1 unit of the actual roughness 95% of the time. The average obtained from the total number of passes is used as the representative value for that data set.
- Project sections are picked so as to cover the roughness spectrum for existing highway projects. This allows for the results of the correlation to be generalized over this range.
- The use of different profilograph devices for each section, or a combination of devices for each project, is useful in reaching a mean measurement representative of all devices. However, according to an earlier study using the profilograph devices the measurement variability between devices is statistically negligible [4].

In order to make a comparison between the variability of profilometer measurements and that of California profilograph measurements, one can use the coefficient of variation, that is the ratio between the measurement standard deviation and the measurement mean. Using the mean values for the data used in this study, which are 4.13 in/mile for PRI and 66.5 in/mile for Mays index, the respective coefficients of variation are 16.0% for the profilograph and 3.0% for the profilometer.

Number of Project Sections and Lanes

It has been mentioned earlier that one ought to include high, medium and low roughness pavement sections in the study. The selection of pavement sections and the execution of the data collection task for the study were performed as follows;

- A total of 12, 0.1 mile sections representing the appropriate highway roughness levels were included.
- Existing data were used to pick one of the sections in each of the selected projects. The selection of the remainder of the 0.1 mile sections was left to the people involved - depending on operational convenience at the time of the measurements.
- A total of five roughness measurements (replicates) were made for each wheel path for each selected 0.1 mile section of a project. The mean of the replicate values for the 0.1 mile section constituted one data point for the analysis.
- It was initially considered desirable that more than one operator take part in the data collection, using the profilograph devices. The decision to use only one profilograph device was based on the preliminary nature of this phase of the study. For the same reason, a single operator was used in the collection of the data.

Data Collection

The data collection plan resulted in a total of 12 data collection sections for the analysis (6 projects x 2 sections/project). While this was not a large number of data sets for statistical purposes, it was considered sufficient for the preliminary task of establishing whether the profilometer and profilographs could indeed be linearly correlated. It should be noted that each of the twelve sections had two wheel paths and that 5 replicates were collected from each wheel path.

The majority of the data for this study were collected between July 9th and August 20th 1992. Additional data were collected in mid-September, 1992 to replace some data which were inadvertently collected with a faulty profilometer. In most cases California profilograph measurements and profilometer measurements were made on the same day or within a few days. The final breakdown of projects included in the data collection, and the number of sections used from each project are as follows;

- Loop 101: University - Southern, 4 sections
- SR 360 - Ellsworth 3 sections
- SR 51: Glendale - Northern, 2 sections

- I10: 99th Avenue - 115th Avenue, 2 sections
- SR 143: Washington - Sky Harbor, 1 section

- **Total Number of 0.1 mile sections =** **12**

For each section, ten (10) measurements were taken using the California profilograph (5 for each wheel path). The average of these measurements was computed, which was used for the correlation study as representing the pavement roughness index (PRI) for that section as measured by the profilograph device. With the profilometer, three repeat measurements were made, for which the average of the three was again used as the measured Mays index or IRI index for the correlation. In this case profile measurements for both wheel paths are computed simultaneously. Only in the case of the IRI is an index computed by the computer system for the individual wheel paths. Table 3 shows a sample of the data collection sheet used for this exercise.

TABLE 3. DATA COLLECTION SHEET FOR ROUGHNESS MEASUREMENTS

	SECTION / STA.		DEVICE	profilograph PASS # / INDEX		profilometer Mays PASS # /INDEX	
PROJECT	FROM:	TO:	ADOT #	LEFT	RIGHT	*BOTH*	OPERATOR(S)
SR-360 W/B	SECTION #1			1	1	1	
	1019+49	*1013+21*		2	2	2	
	LANE 1			3	3	3	
				4	4		
				5	5		
(LOW)	SECTION #2			1	1	1	
				2	2	2	
				3	3	3	
				4	4		
				5	5		

Rejection of Some Profilometer Data

Upon receipt of the data, it were summarized and counter-checked for any obvious problems. Three sets of profilometer roughness measurements raised serious concern for two reasons;

- The differences in the readings between the right and left wheel paths were uncharacteristically high. These are shown in Table 4 below.

- When compared to profilometer readings taken four months earlier on the same highway sections, there were about 50% to 100% differences in the observed Mays/IRI index values. This was in contrast to most of the other sections for which the differences in magnitudes between the data sets were less than 5%.

The scatter plot for IRI Vs PRI (left wheel path) for the complete set of data is shown in Figure 9. The three data points in question can be identified on Figure 9 as those with PRI values less than 4 but with IRI values greater than 120, clearly isolated from the trend shown by the rest of the data.

After a review of the suspect data sets and the historical records of the profilometer performance, it was determined by the Materials Section of ADOT that the sensor on the left wheel of the profilometer had malfunctioned during the collection of the data set. Therefore new roughness data were collected to replace the suspect data. The new data showed no major discrepancy between the two wheel paths and were similar to the values obtained four months earlier. At this point it was decided to exclude the suspect data from any further analysis.

TABLE 4. LEFT AND RIGHT WHEEL PATH IRI VALUES FOR PROBLEM DATA

Section #	Replicate #	Wheel Path IRI (in/mile)		Difference Between LEFT & RIGHT
		LEFT	RIGHT	
1	1	166.2	66.7	99.5
	2	158.5	66.7	91.8
	3	161.0	66.4	94.6
2	1	175.0	68.0	107.0
	2	158.6	65.2	93.4
	3	163.6	65.3	98.3
3	1	138.4	69.6	68.8
	2	140.8	68.1	72.7
	3	145.3	72.7	72.6

TABLE 5: AUGUST 1992 AND APRIL 1992 MAYS INDEX VALUES FOR PROBLEM DATA

Section #	April 1992 Reading	August 1992 Reading	Difference: Observed Increase	% Increase April 92 to August 92
1	64.40	97.07	32.67	50.7
2	55.90	98.33	42.43	75.9
3	45.20	86.90	41.70	92.3

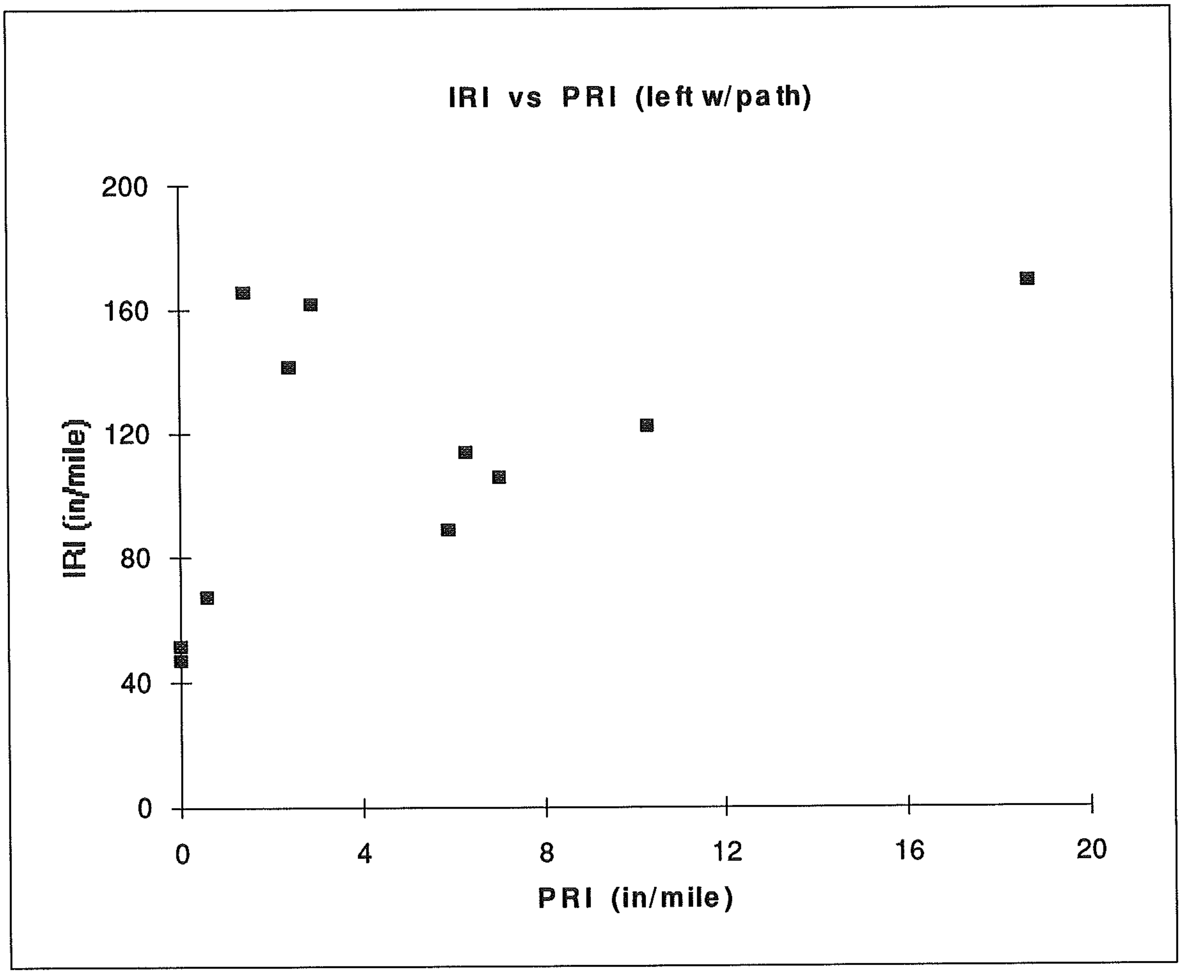

Figure 9. Scatter Plot of IRI against PRI (left wheel path) Showing Rejected Data

CHAPTER 4

DATA ANALYSIS AND RESULTS

Data analysis was performed with a view to establish underlying correlation between the following sets of roughness measures as obtained using equipment within ADOT:

- Mays Index with PRI (both wheel paths),
- IRI Index with PRI (both wheel paths),
- IRI Index with PRI (respective left wheel paths), and
- IRI Index with PRI (respective right wheel paths).

Based on literature from related previous studies [1, 3], the focus of the study was on the establishment of linear correlation between the above sets of measures. The steps that were generally taken in this analysis were as follows:

- Inspection of appropriate scatter plots
- Simple linear regression analysis of those variables
  - study pattern of residual plots
  - develop predictive function
- Investigate possible improvements with the addition of quadratic terms in the regression functions.

Scatter Plots. All four scatter plots suggested the existence of a linear relationship between the variables. In particular, the scatter plots for Mays against PRI, IRI against PRI (both wheel paths) and IRI against PRI (left wheel path) had a distinctive linear trend, with the data points falling within a very narrow band on the trend line. The scatter plot for IRI against PRI (right wheel paths) was more spread out in comparison to the other three.

Regression Analysis. A simple linear regression procedure was used which employs the method of least squares. This method determines the regression line as that which minimizes the sum of squared vertical distances from the observed data points to the regression line. The computer statistical package SPSS/PC was utilized for the analysis.

Summary of Regression Results

Table 6 gives the summary of regression equations from the analysis. Residual plots were studied to see whether there were any indications of violation of the linear regression assumptions of 1) Normality, 2) Equality of variance, 3) Independence and 4) Linearity. In all cases there was no evidence of the violation of these assumptions. For a treatment of residual analysis in linear regression, some statistical references are included at the end of the report [10, 11]. Scatter plots for the regression of profilometer index values against PRI, showing the respective regression lines are given in Figures 10 to 13. Prediction confidence intervals for Mays Index values (3 and 5 replicates) at the 95% level, are shown in Table 7. Residual plots appear in appendix B.

TABLE 6. REGRESSION EQUATIONS FOR THE INDEX VARIABLES

Dependent Variable (index)	Independent Variable (index)	Regression Equation	Coefficient of Determination (R^2)
Mays	PRI (both wp)	Mays = 43.3 + 5.7 * PRI	0.95
IRI (both wp)	PRI (both wp)	IRI = 52.9 + 6.1 * PRI	0.93
IRI (left wp)	PRI (left wp)	IRI = 53.5 + 6.6 * PRI	0.95
IRI (right wp)	PRI (right wp)	IRI = 54.5 + 5.0 * PRI	0.68

Note: '**wp**' used for "wheel path".

Effect of the Number of Replicates

The expression below was used earlier to compute the error of estimate, E.

$$E = \frac{t_{\alpha/2,n-1} * s_r}{\sqrt{n}}$$

The value of E is equal to half of the confidence interval which contains the parameter estimate for a given confidence level α, for the profilograph measurements. Using the data in this study, the repeatability standard deviation was evaluated as 0.534 in/mile. A plot of E, the normalized confidence interval, against the number of replications n, as evaluated above, is shown in Figures 14 and 15 for 90% and 95% confidence, respectively.

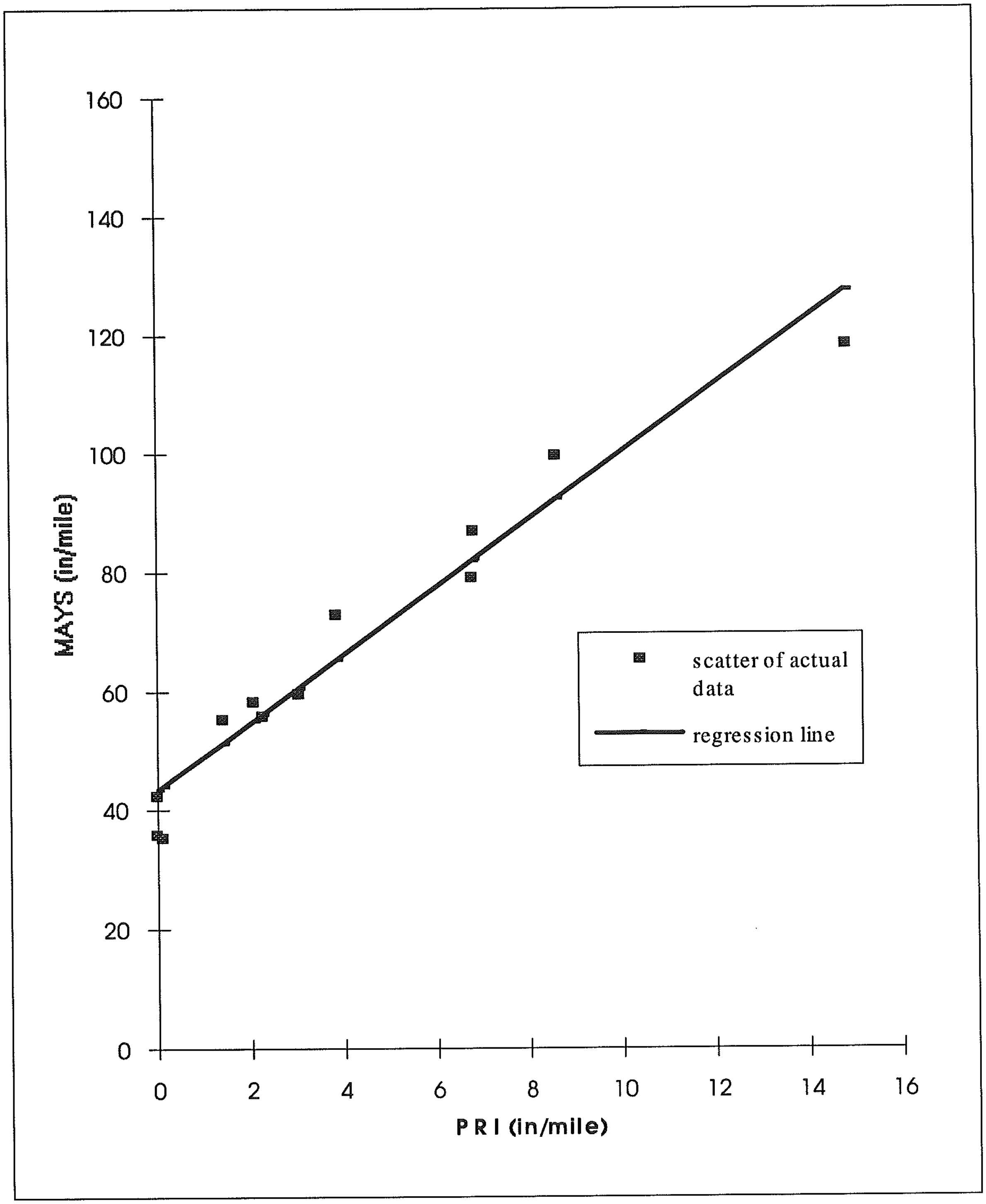

Figure 10. Scatter plot of Mays Index vs. PRI (both wheel paths) Showing Regression Line

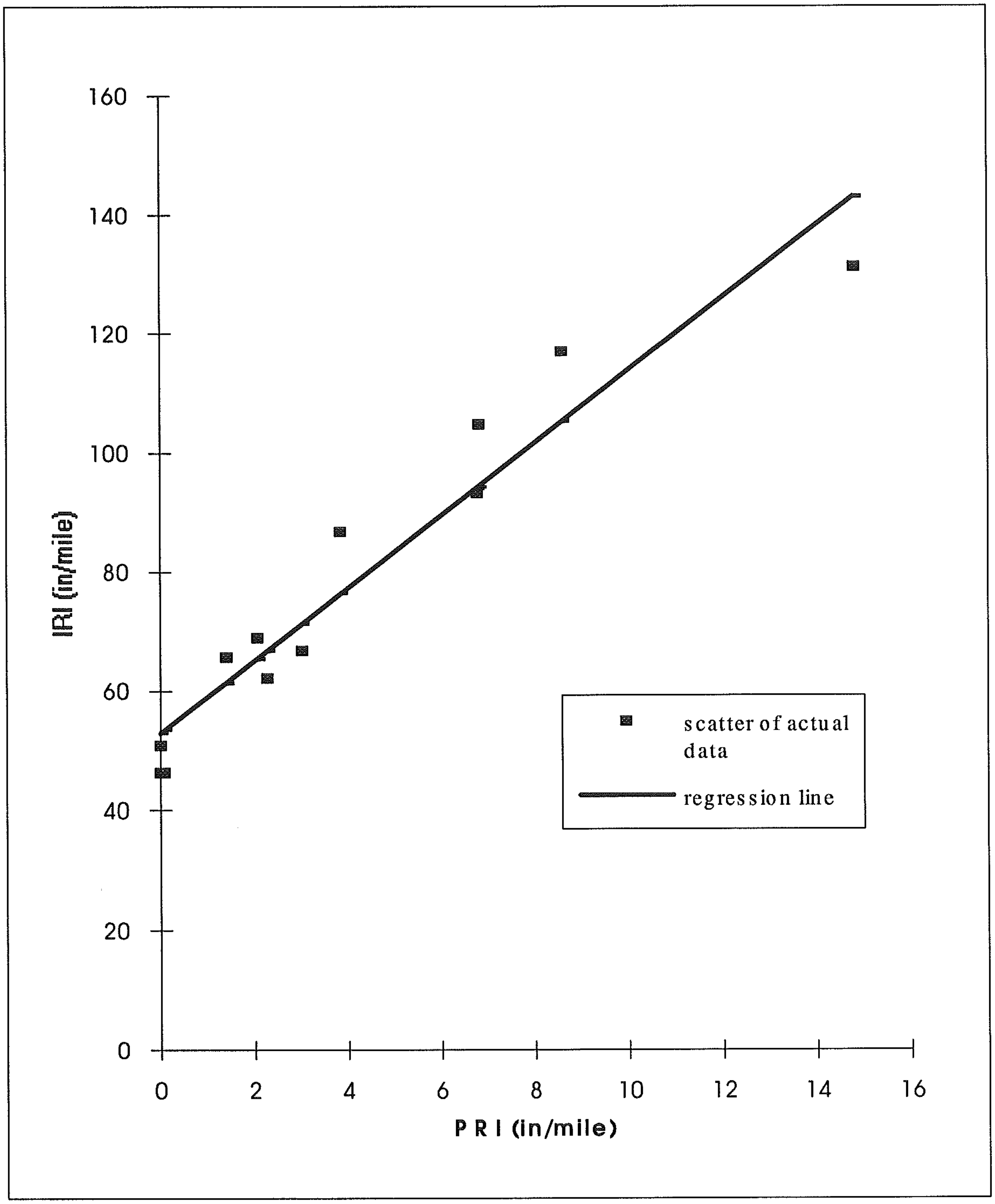

Figure 11. Scatter plot of IRI vs. PRI (both wheel paths) Showing Regression Line

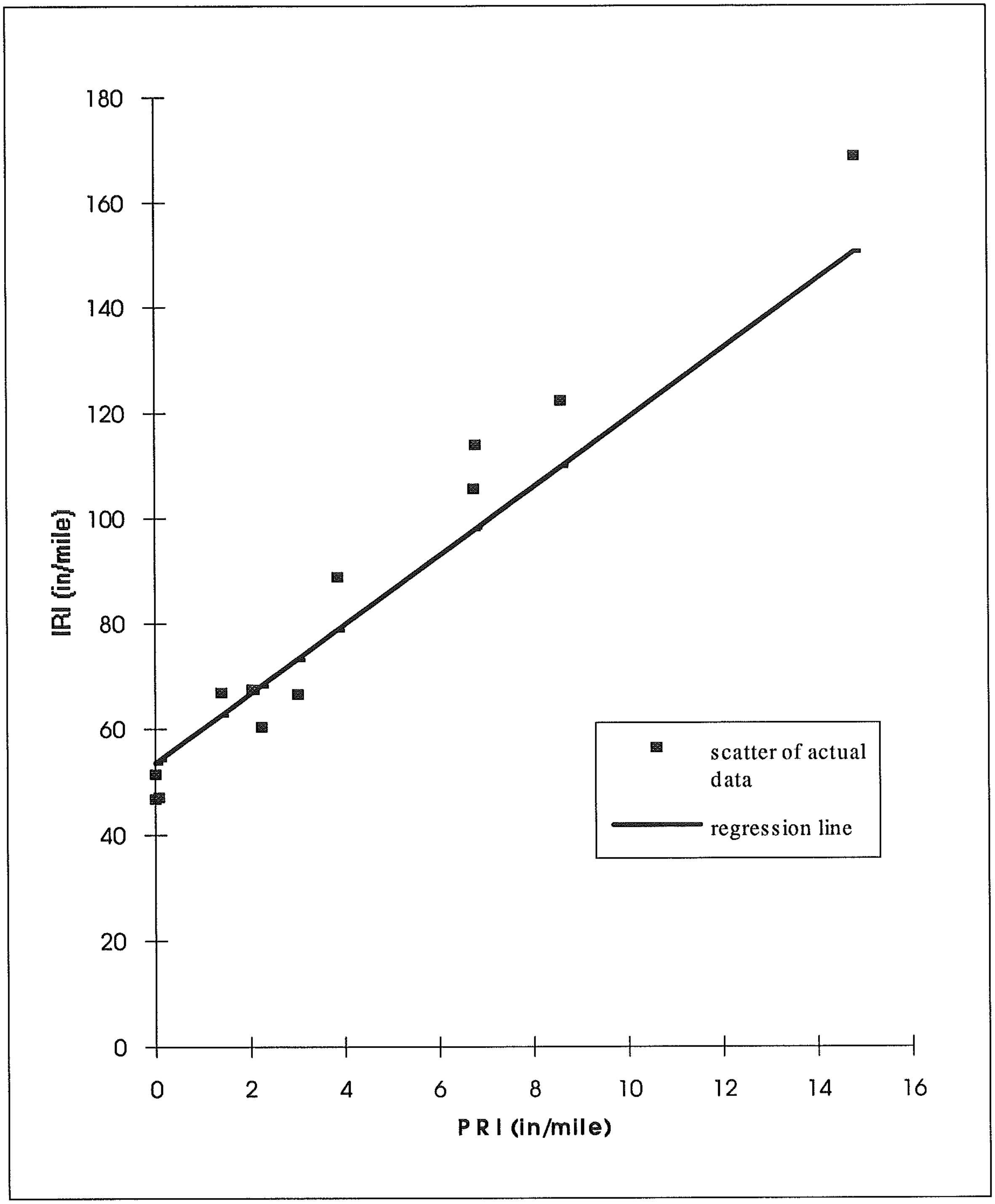

Figure 12. Scatter plot of IRI vs. PRI (left wheel path) Showing Regression Line

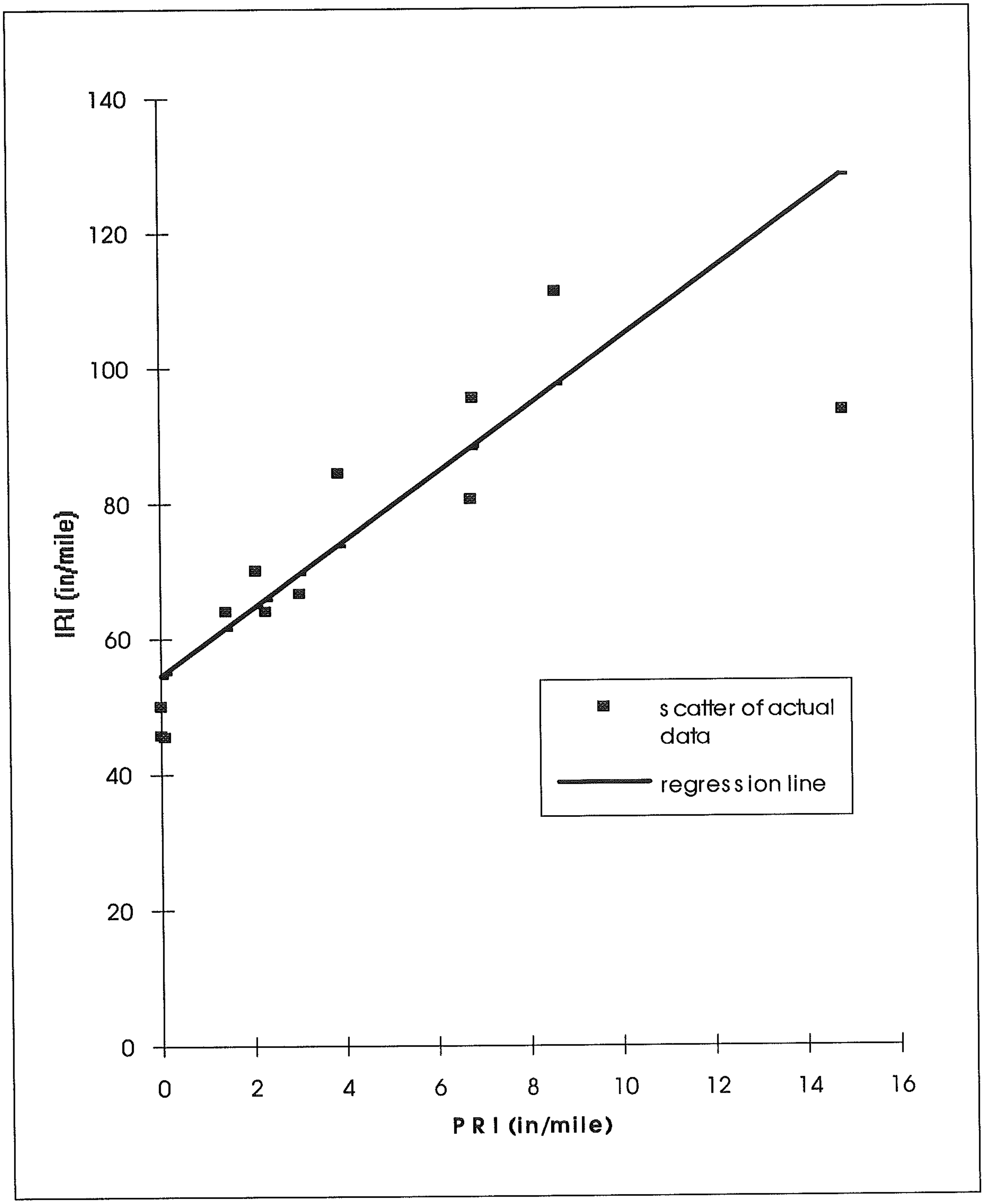

Figure 13. Scatter plot of IRI vs. PRI (right wheel paths) Showing Regression Line

TABLE 7. MAYS INDEX PREDICTION CONFIDENCE INTERVALS WITH 3 AND 5 PROFILOGRAPH MEASUREMENT REPLICATES

PRI (in/mile)	PREDICTED MAYS INDEX (in/mile)	95% CONFIDENCE LIMITS			
		3 REPLICATES		5 REPLICATES	
		LOWER	UPPER	LOWER	UPPER
0	43.3	33.5	53.1	34.9	51.7
1	49.0	39.6	58.4	41.0	57.0
2	54.7	45.5	63.9	47.0	62.4
3	60.4	51.4	69.4	52.9	67.9
4	66.1	57.1	75.1	58.7	73.5
5	71.8	62.8	80.8	64.4	79.2
6	77.5	68.4	86.6	69.9	85.1
7	83.2	73.8	92.6	75.3	91.1
8	88.9	79.2	98.6	80.6	97.2
9	94.6	84.5	104.7	85.9	103.3
10	100.3	89.7	110.9	91.0	109.6
11	106.0	94.9	117.1	96.1	115.9
12	111.7	100.0	123.4	101.2	122.2
13	117.4	105.1	129.7	106.2	128.6
14	123.1	110.1	136.1	111.2	135.0
15	128.8	115.1	142.5	116.1	141.5

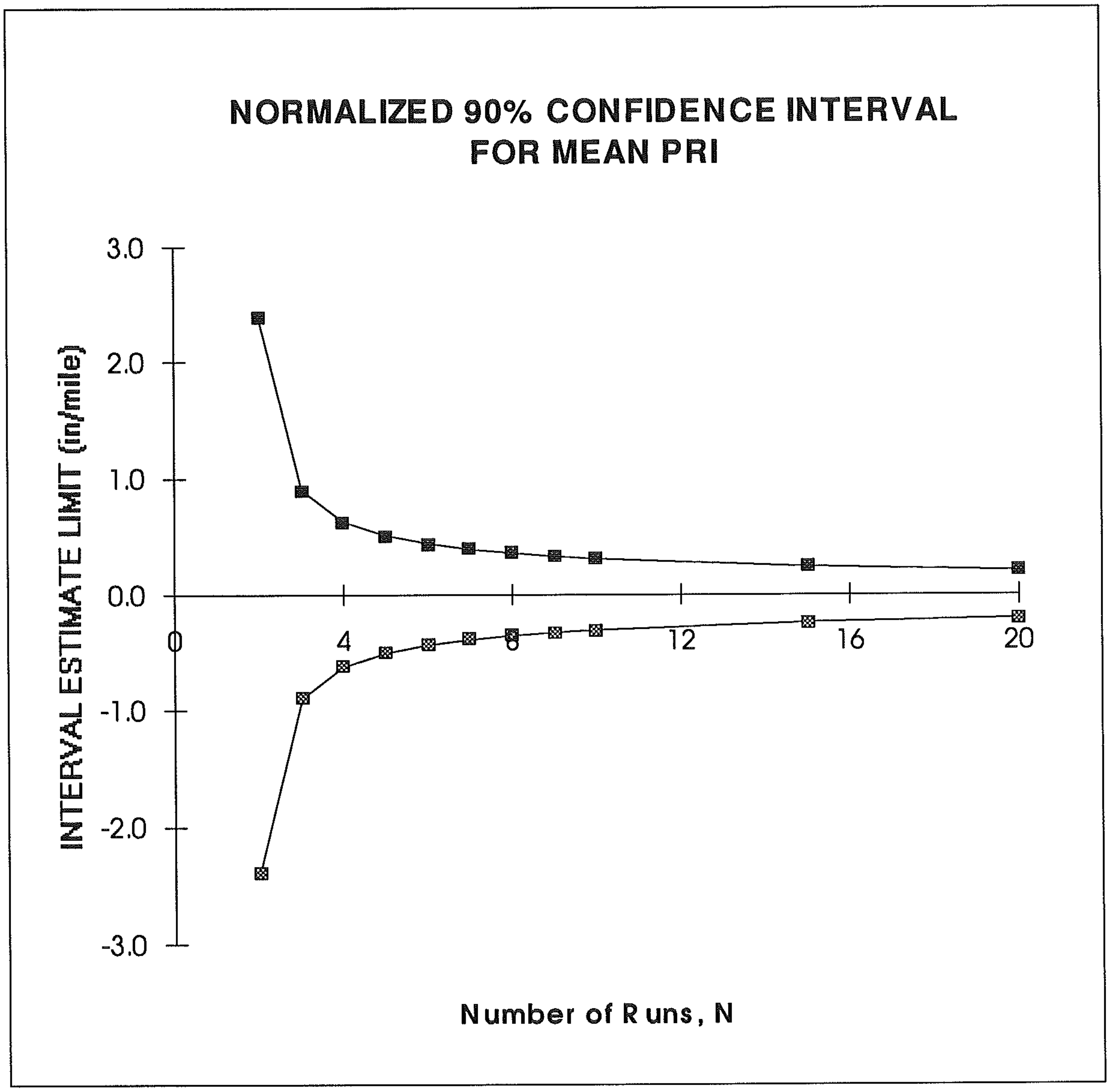

Figure 14. Variation of Normalized 90% Confidence Interval in PRI for Different Numbers of Replicates

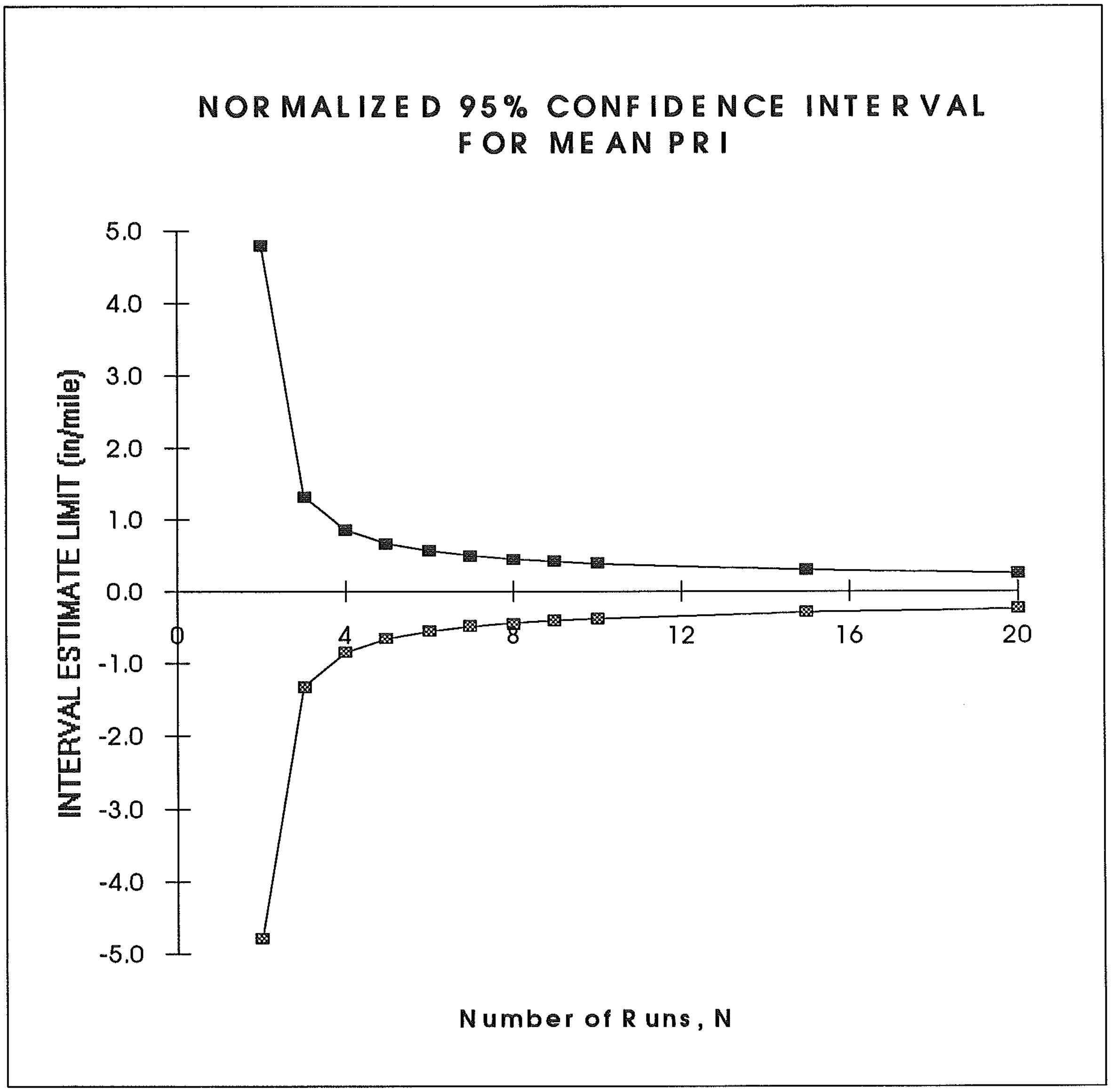

Figure 15. Variation of Normalized 95% Confidence Interval in PRI for Different Numbers of Replicates

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The evaluation of the PTI programs was made in an attempt to find a possible calibration procedure for the California profilograph devices. If a feasible procedure utilizing an easy-to-build profile model was successfully tested, it would have provided a convenient method for profilograph calibration. The data required by the profilograph simulation program, a stream of profile elevations at 6 inch intervals, cannot be down-loaded from ADOT's profilograph devices as these devices do not currently have a provision for such down-loading. These devices compute a profilograph index for the 0.1 mile section at the end of the run. On the other hand, test results obtained using the profilograph index computation program did not agree with stated values [1].

Direct use of profilometer profile data in conjunction with the profilograph index computation program was not possible because of differences in data format requirements. Index values computed using the program after modifications addressing the differences in data format, were seen to be about 50 percent higher than expected values. Therefore, the direct use of the existing PTI program and profilometer data for profilograph calibration is not possible

It has been shown in this study that a linear relationship exists between California profilograph index values and profilometer Mays or IRI index values. Ideally, the regression lines as given in Chapter 4 should be used with values for the respective indices averaged from the same number of replications as was used in the study. This calls for 5 replications for profilograph measurements and 3 replications for profilometer measurements. If fewer profilograph measurements are used due to time constraints, at least 3 replications are recommended. In such cases one must keep in mind the fact that the expected error with the smaller samples is higher than the expected error with samples of 5.

The observed correlation between PRI values and Mays/IRI values can be used with actual profilometer and profilograph measurements for an approximate profilograph calibration. The underlying assumption that governs the use of a profilometer to calibrate profilographs is that the profilometer is well calibrated using other procedures, and that it has the desired accuracy for measuring pavement roughness index. Using the regression lines developed in the study, a 95% confidence interval for a mean PRI from three measurements, given a profilometer Mays index, was developed and plotted for Mays index values from 40 to 120 in/mile. The confidence intervals imply that one expects the mean PRI from a set of three profilograph measurements, for a given Mays index value to fall within the corresponding confidence limits 95 percent of the time. A profilograph device that repeatedly yields sample means outside of this interval would be showing signs of a calibration problem. A plot of the 95% confidence interval for predicting PRI mean values for samples of 3, given a profilometer Mays index, appears in appendix C.

In using the results of the correlation study, it appears appropriate to use average wheel path index values from profilometer and profilograph measurements. For the profilometer, these values are either the Mays index or the IRI (both wheel paths). Before these results can be used with all profilograph devices within ADOT, if so desired for quality control and acceptance purposes, a similar analysis is needed that will use all such devices to verify the validity of a single regression function for the profilograph devices.

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APPENDICES

APPENDIX A

Description of PTI Profilograph Index Computation Program

Program Units

The simulation program is made up of six main units:

- MAIN program,
- subroutine MOVAVG,
- subroutine COUNTIPM,
- subroutine UPPER,
- subroutine LOWER,
- and subroutine FNAME.

Program Files

For each program execution, the user is required to supply three file names, one an input file - the master file (must actually exist at program execution), and the other two are output files. These can be considered as 1) the master file, 2) output file number 1, and 3). output file number 2. The specification and format requirements for these files are as follows.

Master file and data files: the name of the master file is to be entered when queried to "input file name to be processed". The full name with extension should be supplied. This has to be an existing file whose contents are data file names. Each of the data files to be processed, should occupy one row in this file. The data file names in the master file should be entered without their extension (e.g. srb342 for the file srb432.dat). Note that the actual data file names should always have the extension '.dat'.

Output file 1 and output file 2: The program is configured to write output into two different files. In response to the two queries, 'file name for counting history' and 'file name for IPM listings', the names for the two data files, complete with extensions, should be supplied. These files need not be existing, they will be created as new files if they do not exist.

Program Execution

Figure 1 of the report showed a block diagram of the computer program. Each of the program units is described below.

MAIN program: Within the main program key parameters like the blanking width and the truss length are assigned values. The relevant input and output files are defined and opened with the appropriate file names. After reading a data file name from the master file, the subroutine FNAME is called. This subroutine constructs the complete data file name with the extension '.dat'. Profile elevations are read to the array PROFL(J) and the total distance evaluated based on the total number of data points read. At this point the main program calls the subroutine MOVAVG. Upon return of control from this subroutine, the following assignments are made;

- an array of differences, PROFD(J) = PROFL(J)-PROFC(J) - where PROFC(J) is a smoothed array returned from the subroutine.
- YMEAN=$\sum PROFD(J)/N$
- PROFC(J)=PROFD(J) - YMEAN

  Finally, the main program calls the subroutine COUNTIPM and terminates the program when control is returned, unless there are more data files to be processed.

Subroutine MOVAVG: This subroutine performs a moving average smoothing of the profile elevations with specified average length. The output of this subroutine is an array of after-smoothing profile, PROFC(J).

Subroutine COUNTIPM: This subroutine counts the inches per mile index for the provided road profile. The array used by this subroutine is PROFC(J) , evaluated in the main program. The two subroutines UPPER and LOWER are used from this program unit for determining roughness contributions from the profile elevations. The profile index and other summary values are output to the relevant output files from this subroutine.

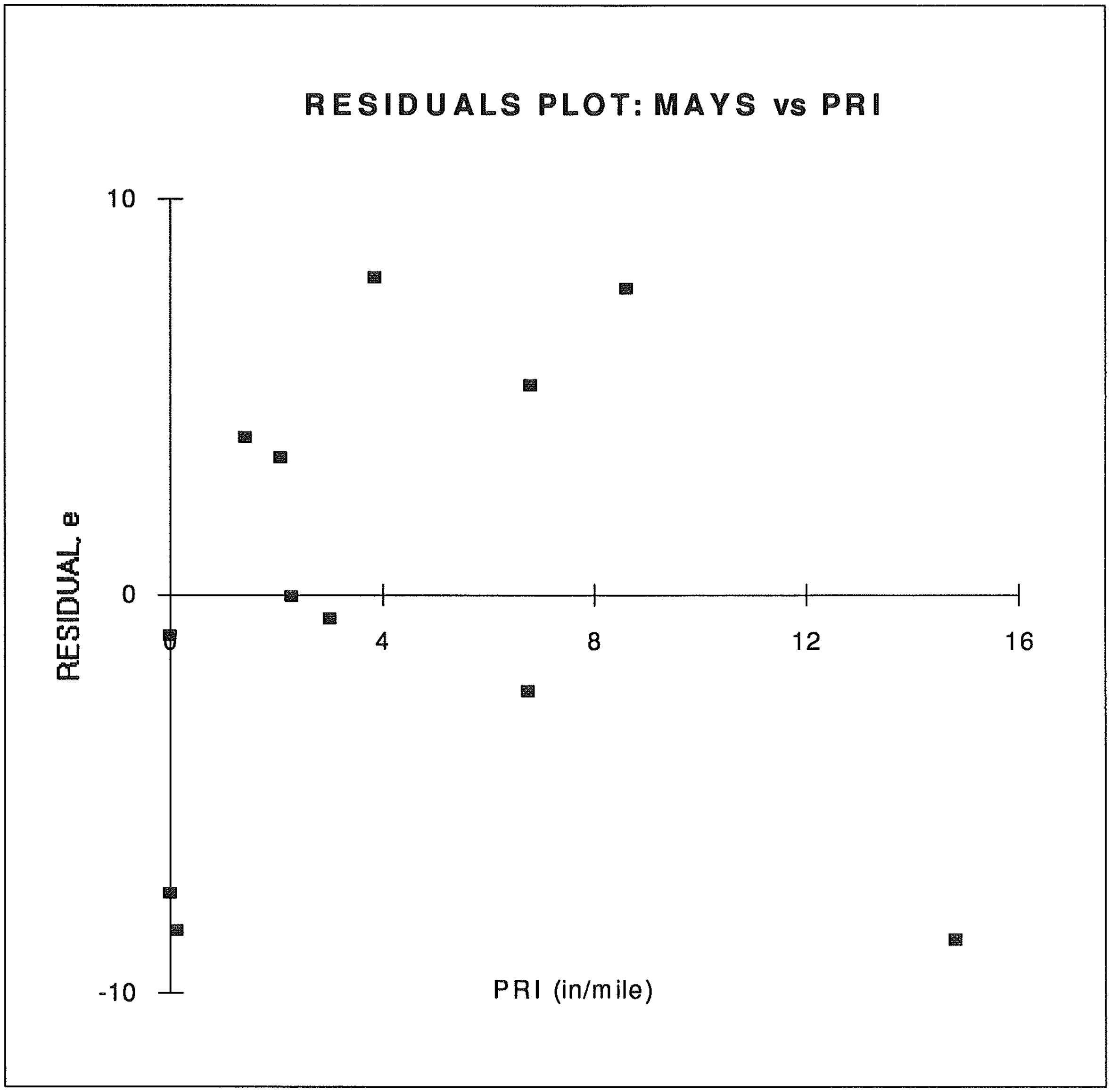
Subroutine UPPER: For determining whether or not the upper portion of a profile section contributes to roughness, the subroutine UPPER is used. It compares the values on the top part of a profile with the applicable blanking band.

Subroutine LOWER: This subroutine determines whether or not the lower portion of a profile section contributes to roughness, by making value comparisons to the lower blanking band.

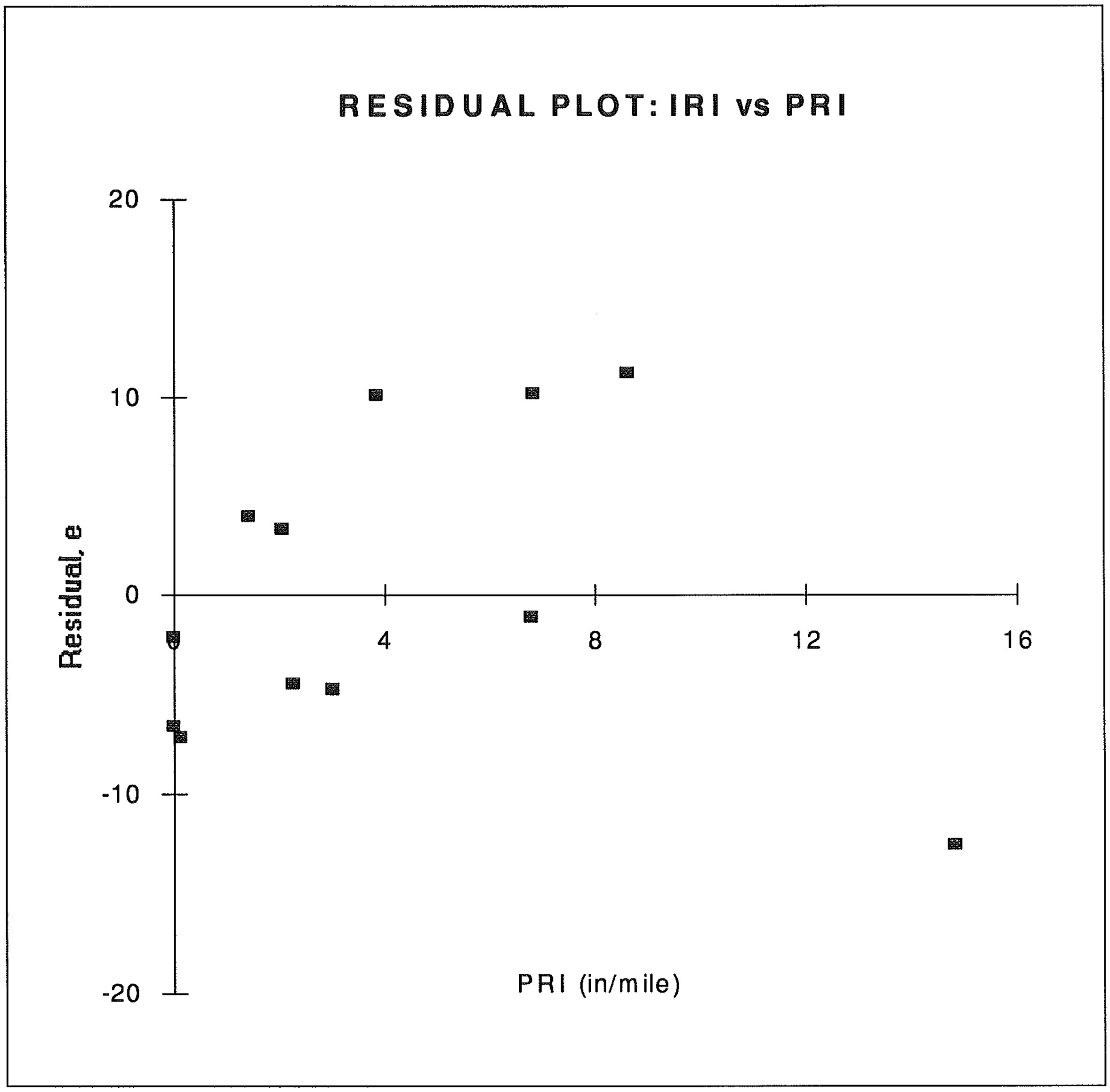
Subroutine FNAME: The subroutine FNAME appends the extension ".dat" to data file names read from the master file (called 'file to be processed'). The data file names in the master file should have no extensions. If, for instance, the name ROAD1 is read, a data file name is constructed as ROAD1.DAT. This data file ('ROAD1.DAT') should exist, or else an error message will result.

APPENDIX B

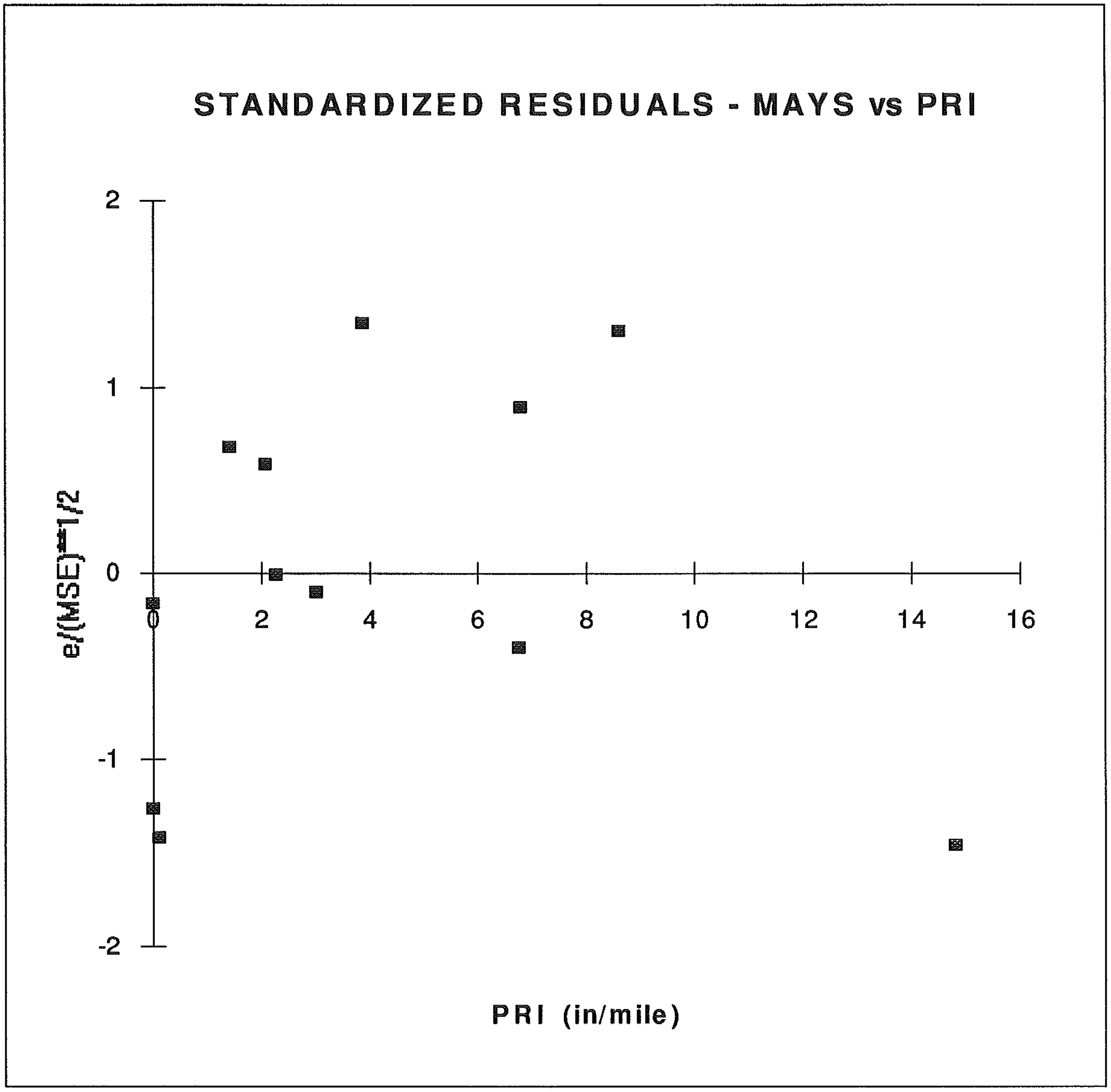
Residual Plots for the Regression Variables



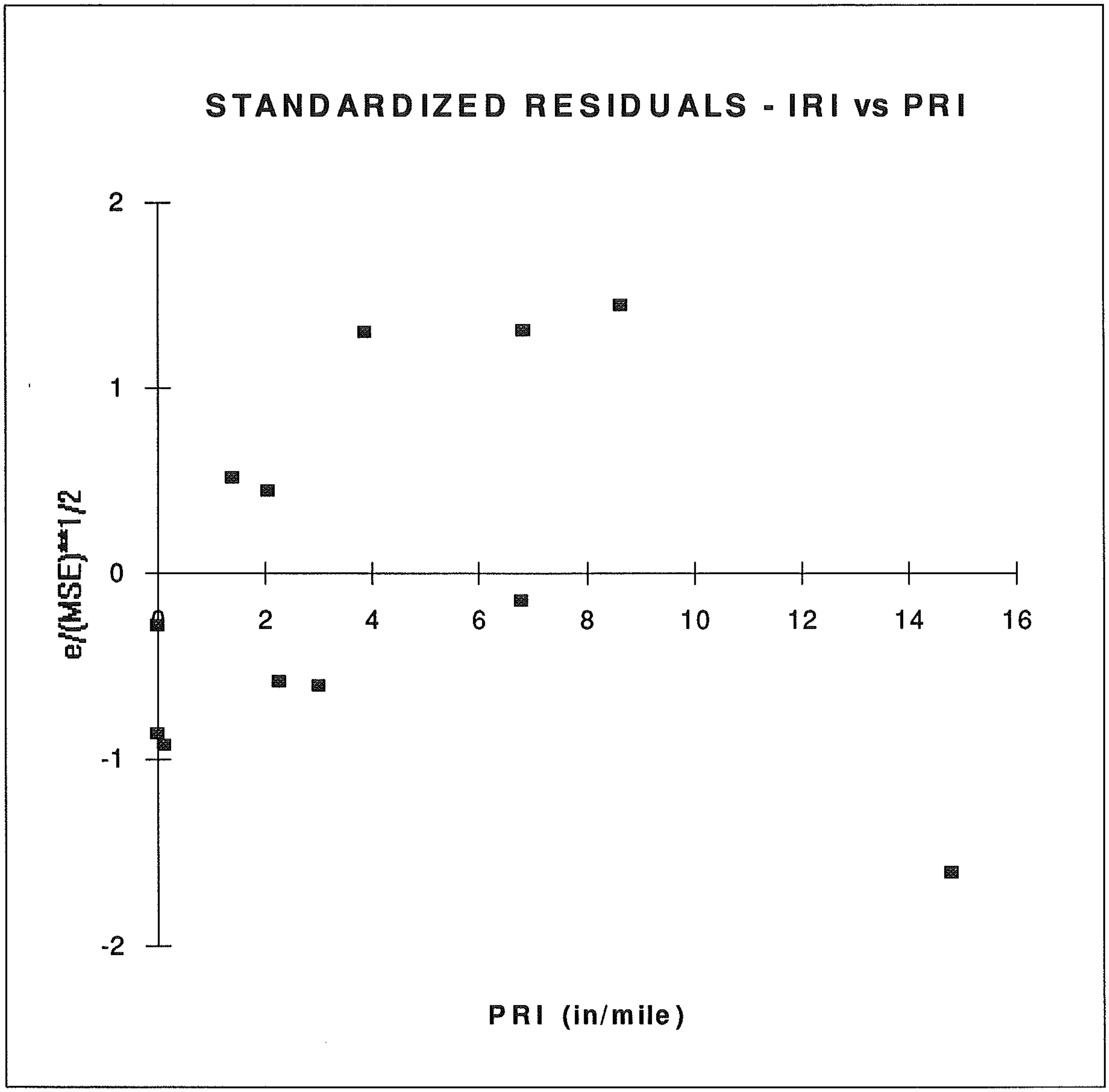
NB: The Residual, e = measured 'y' value - expected (regression) 'y' value for the 'x' value



NB: The Residual, e = measured 'y' value - expected (regression) 'y' value for the 'x' value



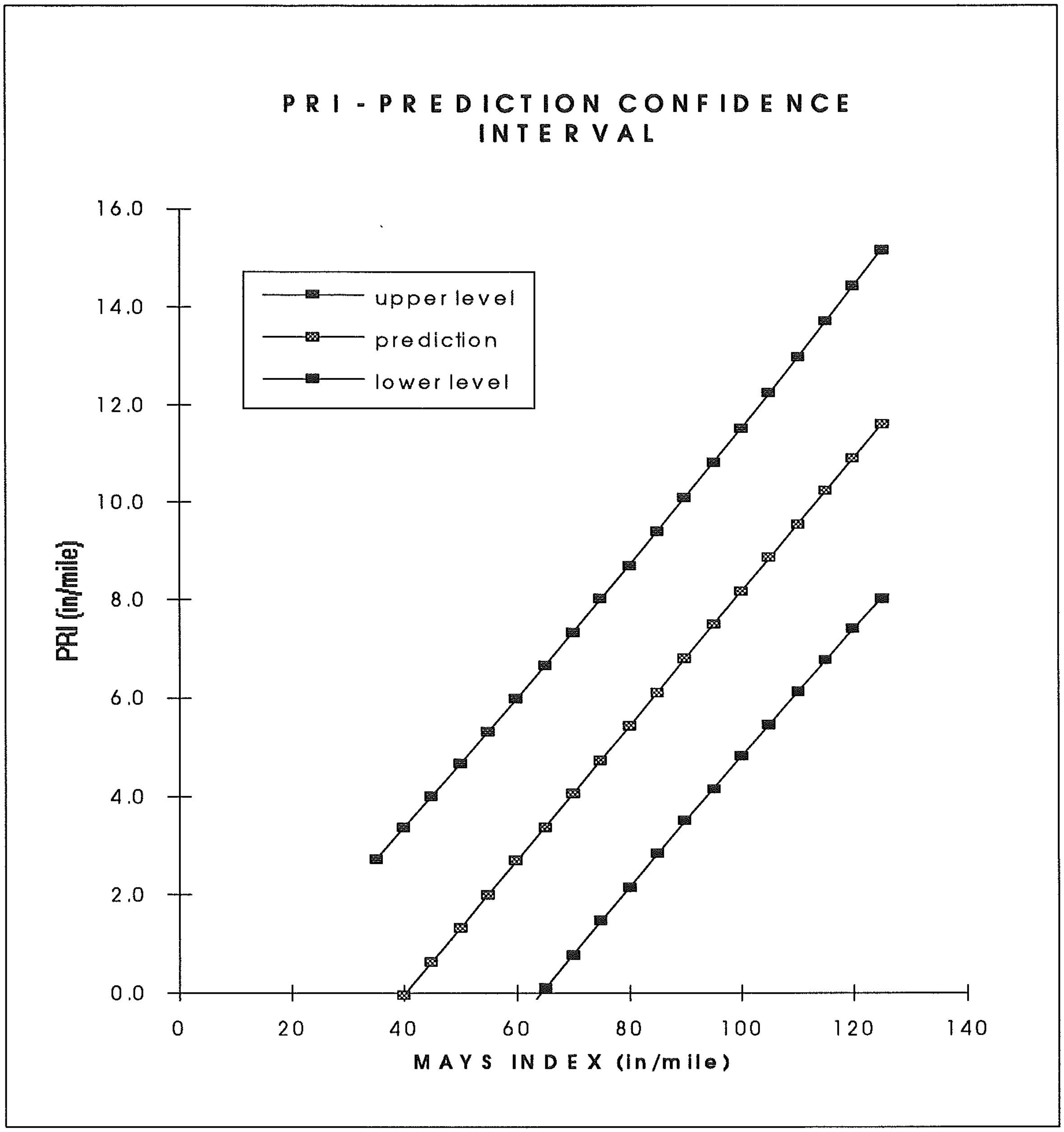
NB: The Residual, e = measured 'y' value - expected (regression) 'y' value for the 'x' value
The Mean Square Error, MSE = Variance of Residuals, & (MSE1/2) = Std. Dev. of Residuals**



NB: The Residual, e = measured 'y' value - expected (regression) 'y' value for the 'x' value
The Mean Square Error, MSE = Variance of Residuals, & (MSE1/2) = Std. Dev. of Residuals**

APPENDIX C

Confidence Interval for the Predicted Mean PRI Value, Given Profilometer Mays Index



APPENDIX D

Profilograph and Profilometer Data

Section Number ..	1	2	3	4	5	6	7
Project ..	L101 Univ-Southern				S R - 3 6 0		
Station / From ..	2951+82 to	2983+66 to	2978+38 to	2999+34 to	1007+93 to	1013+21 to	1018+49 to
/to ..	2957+10	2978+38	2973+10	3004+62	1002+65	1007+93	1013+21
Direction ..	N/B	S/B	S/B	N/B	W/B	W/B	W/B
Lane Number ..	1	1	1	1	1	1	1
California Profilograph Index, Left Wheel Path (Replicates 1 - 5)	0.70	0.30	0.15	0.05	0.00	0.00	0.00
	0.60	0.30	0.15	0.05	0.00	0.00	0.00
	0.45	0.35	0.15	0.10	0.00	0.00	0.00
	0.70	0.25	0.10	0.05	0.00	0.00	0.00
	0.50	0.25	0.15	0.05	0.00	0.00	0.00
California Profilograph Index, Right Wheel Path (Replicates 1 - 5)	0.20	0.30	0.25	0.25	0.00	0.00	0.05
	0.15	0.30	0.35	0.20	0.00	0.00	0.00
	0.10	0.30	0.30	0.20	0.00	0.00	0.00
	0.20	0.35	0.30	0.20	0.00	0.00	0.00
	0.25	0.30	0.35	0.25	0.00	0.00	0.05
Profilometer Mays Index Values (Replicates 1 - 3)	73.1	59.7	55.7	55.0	41.9	36.5	35.7
	72.5	59.2	56.5	55.0	42.8	35.9	35
	73.7	60.1	55.7	55.7	42.2	35.0	35.6
Profilometer IRI Values Left Wheel Path (Replicates 1 - 3)	91.1	66.6	60.8	67.5	53.9	44.1	48.4
	92.2	65.3	61.4	67.3	47.7	47.4	45.5
	83.1	67.6	59.1	66.1	52.6	48.5	47.6
Profilometer IRI Values Right Wheel Path (Replicates 1 - 3)	82.0	68.3	63.3	64.2	48.6	49.3	47
	82.3	65.8	64.3	64.1	53.6	46.7	44.6
	89.1	66.2	64.4	63.9	48.1	41.5	44.9

Profilograph and Profilometer Data (continued)

Section Number ..	8	9	10	11	12
Project ..	**SR-51 GLE to NOR**		**I10 99th to 115th Ave**		**WASHINGTON SKY-HARBOR**
Station / From ..	16+01 to	21+29 to	7015+84 to	7021+12 to	47+00 to
/to ..	21+29	26+57	7021+12	7026+40	52+28
Direction ..	N/B	N/B	W/B	W/B	W/B
Lane Number ..	3	3	4	4	1
California Profilograph Index, Left Wheel Path (Replicates 1 - 5)	1.15 0.95 1.05 0.90 1.10	0.80 0.55 0.75 0.50 0.55	1.55 2.05 1.95 2.00 1.80	0.85 0.60 0.65 0.75 0.65	0.25 0.10 0.20 0.35 0.30
California Profilograph Index, Right Wheel Path (Replicates 1 - 5)	0.60 0.70 0.65 0.70 0.80	0.65 0.85 0.70 0.70 0.75	1.05 1.10 1.10 1.20 1.00	0.70 0.60 0.65 0.60 0.70	0.20 0.20 0.20 0.15 0.10
Profilometer Mays Index Values (Replicates 1 - 3)	98.2 100.6 100.3	87.5 86.8 87	121.7 118.0 115.6	79.8 80.0 77.5	58.8 57.7 58.7
Profilometer IRI Values Left Wheel Path (Replicates 1 - 3)	120.5 122.7 123.8	114.7 113.2 113.6	173.5 168.6 164.0	105.8 107.8 103.2	68.3 68.0 66.5
Profilometer IRI Values Right Wheel Path (Replicates 1 - 3)	109.7 111.9 112.6	96.5 95.4 95.2	94.0 92.5 94.4	81.2 79.2 81.7	69.9 70.2 70.2